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TM-04101

COMPARATIVE PERFORMANCE EVALUATION OF DIGITAL DATA MODEMS FOR HF RADIO

TECHNICAL DOCUMENTARY REPORT NO. ESD-TDR-64-631

JANUARY 1965

R. E. Greim
W. R. Menges
F. N. Nelson, Jr.

Prepared for

DIRECTORATE OF AEROSPACE INSTRUMENTATION
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

Project 705.1

Prepared by

THE MITRE CORPORATION
Bedford, Massachusetts
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FOREWORD

The successful conduct of the modem evaluation program described herein could not have been accomplished without the cooperation of numerous individuals and organizations who, regrettably, cannot all be mentioned by name because of space limitations.

The Aerospace Instrumentation Directorate of the Air Force Electronic Systems Division provided overall task direction and arranged for overseas transportation of equipment. The Air Force Missile Test Center Liaison Office (AFMTCLO) in Pretoria handled all arrangements regarding the use of South African Ministry of Posts and Telegraphs radio transmitting facilities, transportation of equipment in South Africa and staff living facilities in Pretoria.

The operating personnel at Radio Transmitting Station, Olifantsfontein, South Africa, under the direction of Mr. C. R. Maske, were most cooperative in connecting the test equipment and operating the radio transmitting equipment so as to facilitate our conduct of the tests.

At the Riverhead, Long Island receiver site, the wholehearted cooperation of the RCA operating personnel under the direction of the site manager, Mr. J. M. Etter, did much to help maintain the operating schedule particularly with respect to coordinating frequency changes.

In addition, we wish to acknowledge the cooperation of Collins Radio Co., Northern Radio Co., and Rixon Electronics, Inc., in making their equipment and assistance available for participation in these tests.

Finally, we wish to acknowledge the MITRE test personnel in the field, including J. D. Bosia, S. J. Forde, Jr., R. W. Gilliatt, L. J. James, R. M. Steeves, P. E. Wagner, and R. Wilson, who, by their willingness to maintain a protracted, arduous, shift schedule, were responsible for the considerable amount and quality of the data collected.

ABSTRACT

The comparative performance of several digital data modems over a high-frequency (HF) radio link is described in this document. During April and June 1964, field testing of evaluation models of new phase-shift keyed (PSK) modems was conducted over a leased 6900-nautical mile HF radio circuit from Pretoria, South Africa, to Riverhead, New York. The superior bandwidth economy of PSK over frequency-shift keyed (FSK) modulation was demonstrated. This work was accomplished as part of the ESD program to improve missile test range HF digital data transmission.

<u>REVIEW AND APPROVAL</u>

This technical report has been reviewed and is approved.

for Clement V. Horrigan
ROY D. RAGSDALE
Colonel, USAF
Director, Aerospace Instrumentation

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TABLES

SECTION I

INTRODUCTION

DATA TRANSMISSION REQUIREMENTS

The increase in the scope and extent of missile and spacecraft test activity has been paralleled by an increase in the burden to be borne by the communications networks of the National Ranges. Not only is an expanded communications capability desired merely to provide increased capacity, but new techniques must be developed which allow communications with improved data quality and with greater reliability.

These requirements for expansion and improvement of techniques, especially in the area of long-haul communications, have resulted from the change in scope of the new programs and the shift in the center of range interest. The new programs (long-range ballistic missiles, satellites, space probes, and manned-space craft) have shifted the center of interest from the launch area (Cape Kennedy) to those points which monitor such important functions as orbit injection, orbit status, and reentry parameters. The increased emphasis on centralized control inherent in these activities is demanding an improved real-time communication capability to be provided between the launch area and the down-range sites (South Atlantic Ocean, African and Indian Ocean stations).

Typical data transmissions requirements include such items as:

(a) Precision Tracking Data: High-Density Data Transmission (HDDT) of RAET* at 2880 bits/second from AN/FPQ-6 or TPQ-18 type radars at Ascension Island and Pretoria, South Africa.

(b) Range Control: One full duplex voice channel for handling high bit rate (3000 bits/second) data. The control functions will be sent down-range from Cape Kennedy to all stations and confirmation reports will be sent up-range.

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*(Range, Azimuth, Elevation, Time coordinates)

(c) Bioinstrumentation: Two voice channels for handling telemetry information stripped from the vehicle telemetry links.

(d) Status and Event Telemetry: Data up-range to central control at rates in excess of 4800 bits/second.

Since the existing submarine cable extends only as far as Antigua (ETR Station 9.1) at present and for the foreseeable future, real-time data transmission with such stations as Ascension (Station 12) and Pretoria (Station 13) will continue to be via high-frequency (HF) radio. The increasing use of range ships (ARIS class) and aircraft will mean continued dependence upon HF radio for data transmission.

Because of the limited radio spectrum in the HF region, pyramiding of present slow data rate equipment is not the solution to the high-speed, long-haul communications problem. Techniques must be developed and implemented which will satisfy the range needs for high-speed, high-reliability, bandwidth economy and relative immunity to the perturbations of the transmission medium.

HISTORICAL BACKGROUND

In an initial attempt to achieve higher data rates throughout the long-range communication systems, data terminal equipments employing modulation techniques found satisfactory for use on wire lines, cable and line-of-sight radio were utilized. The results obtained, however, were unsatisfactory when these techniques were applied to the long-range, HF radio circuits which exist between Cape Kennedy and the down-range stations not served by the submarine cable (Ascension Island, South African, Indian Ocean stations and the ocean range vessels).

Therefore, in order to attain more efficient, real-time, high-speed, digital data transmission and also to combat the anomalous characteristics of the transmission media (the ionosphere), the Air Force Missile Test Center (AFMTC) at Patrick AFB initiated a program whose aim was to develop terminal equipment, called modem (modulator-demodulator), incorporating a modulation technique which would achieve efficient communications when used on a circuit involving ionospheric propagational phenomena.

The original AFMTC Task was (Task 79615 and later Task No. 8938.61) entitled, "Equipment for Real-Time Data Transmission Over Radio Frequency Communications Circuits." During FY63, the responsibility for this task was transferred from AFMTC to the Air Force Systems Command/Electronic Systems Division (ESD) at L. G. Hanscom Field, Bedford, Massachusetts, where it became ESD Task No. 5931.05.

ROLE OF THE MITRE CORPORATION

Within ESD, the Directorate of Aerospace Instrumentation, designated ESRI, assumed responsibility for the task and enlisted the support of The MITRE Corporation for fulfillment of the task requirements. Department D-80 (Communications Systems and Techniques) of The MITRE Corporation was selected to support the task, which was designated a part of Task 705.1 by MITRE.

MITRE conducted a canvas of terminal equipment manufacturers for new techniques applicable to the task, identified those which appeared most promising, and assisted in the preparation of a work statement for development contracts. As a result of this effort, two development contracts were awarded by ESD on 1 July 1963, one to General Atronics Co. (Contract No. AF 19(628)-3281), Philadelphia, Pa., and the other to General Dynamics/Electronics (Contract No. AF 19(628)-3268), Rochester, N. Y., for feasibility models of modem equipment designed for use over long-haul, point-to-point, HF radio links.

Since it was not feasible to rely on laboratory simulation of the circuit characteristics which would be encountered during actual operation, it was decided that the developmental models should be evaluated by MITRE during field tests on an actual radio circuit. The objectives of this evaluation were to determine the relative merits of the two new developmental modems compared to one another and to off-the-shelf systems currently being used in the field.

HF TRANSMISSION PROBLEMS

Digital data transmission over long-haul, HF radio links is subject to difficulties peculiar to ionospheric propagation and to the operating environment of the HF band assignments. The behavior of the HF media is changeable and often difficult to predict. It is subject to diurnal, seasonal, and long-term cyclical changes, as well as sudden ionospheric disturbances, magnetic storms and man-made interference. There are also periods when communications cannot be maintained at all in the HF band (2 to 30 mc/second) and, under such circumstances, no data transmission system is operable. The objective of any HF digital data modem development program, therefore, must be to find solutions to the problems which preclude accurate data transfer during periods when the transmission path is established but marked by anomalous behavior. Some of the phenomena which are the most troublesome to HF digital data transmission are:

(a) atmospheric noise,

(b) Doppler frequency shift,

(c) flat (nonfrequency selective) fading, and

(d) multipath distortion, including

  (1) frequency selective fading (intrasymbol interference),

  (2) intersymbol interference, and

  (3) phase distortion.

An investigation of the problem areas commonly encountered in HF radio communications led to the conclusion that the existing "off-the-shelf" modems were inadequate to meet the requirements of transmitting 3000 bits/second in 3-kc/second bandwidth with a bit error probability of 1×10^{-6} in a multipath fading environment. It was evident that new modulation schemes must be exploited which are relatively invulnerable to ionospheric disturbances. In choosing an optimum modulation system for use over HF radio, one must characterize the medium as accurately as possible, determine the deleterious features and select techniques which either (1) passively obviate or (2) actively compensate for these anomalies.

TASK OBJECTIVES

The long-term goal of the task is to provide a capability of transmitting 3000 bits/second within a 3-kilocycle bandwidth with an error rate of 10^{-6} under conditions of good signal strength.

The salient objective of the MITRE evaluation test program was to determine the effectiveness of the signal processing techniques embodied in the evaluation modems in achieving this goal. The relative value of each modem technique should be determined in the ways described below.

A measurement of effectiveness:

(a) in correcting or compensating for the signal distortion caused by the medium;

(b) on an error-rate basis which has been normalized to the full 3000-bit/second model;

A comparative basis:

(a) sensitivity to each of the various disturbances;

(b) normalized error-rate compared with a standard modem system;

(c) relative reliability.

SECTION II

DIGITAL DATA MODEMS

GENERAL

Modem - Definition and Background

The term "modem" was coined by communicators about a decade or so ago in relation to the transmission of digital data over telephone and wire-line circuits. In general terms, modem (modulator-demodulator) equipment encompasses all modulation-demodulation techniques from a simple on-off teletype key to a complex spread-frequency system, but more specifically indicates modulation-demodulation terminal equipment for digital data transmission within a voice frequency bandwidth regardless of the propagation media (radio or wire). Consistent with the aims of the present task, a fitting definition of the term 'modem' is:

> Modulation-demodulation terminal equipment which processes or operates upon digital data information in such a manner as to affect efficient data transfer, when used with conventional HF radio communications equipment, within the voice frequency spectrum available and the propagation constraints of the transmission media.

Modem Techniques

While many different techniques are incorporated in present modem equipment, in general they are all applicable to any data transmission system regardless of the media employed. That is, modems developed for wire lines and telephone circuits may also be used in microwave, tropospheric scatter, cable and VHF and UHF line-of-sight radio circuits. Because of the many vagaries of the ionosphere (rapid fading, differential multipath delay, sudden ionospheric disturbances, etc.) however, use of the same wire line-oriented modem techniques have proven unreliable when applied to long-haul HF radio circuits. As a result, certain techniques are peculiar to modems designed for use over HF radio circuits.

The high-speed serial bit stream is generally buffered into a number of parallel slow-speed bit streams so that the information symbol duration will be sufficiently long enough to counteract the effects of multipath smearing. The parallel data streams are then applied to many parallel tones (frequency-multiplexing) for modulation purposes so that the total data content can be transmitted within the baseband frequency allocated (generally, a nominal voice bandwidth, 375 to 3025 cycles/second).

While some attempts have been made to transmit data over HF in a high-speed serial manner, these have not been too successful.

The modulation techniques used on HF data modems can be categorized into two general areas: frequency-shift and phase-shift keying (FSK and PSK) techniques.

Frequency-Shift Keyed Systems

In frequency-shift keyed (FSK) systems, each slow-speed, parallel data channel is applied to a frequency-shift tone keyer where the tone output is shifted back and forth between two frequency values (i.e., MARK or SPACE), depending upon the state of the input data. An aggregate signal is formed from all of the tone keyers and is used to modulate the radio transmitter.

At the receiving terminal, the received audio aggregate signal is applied to filters which filter each individual FSK channel. Each channel is then applied to a frequency-shift converter which converts the frequency-shift information into voltage levels which are envelope-detected. As the slow-speed bit streams are detected, they are applied to a parallel-to-serial converter which reconstructs the transmitted high-speed bit stream. Delay equalization across the baseband is necessary to effect center strobe sampling and subsequent conversion back to serial data.

Phase-Shift Keyed Systems

In phase-shift keyed (PSK) systems, the slow-speed parallel channels are used to shift the phase of the frequency-multiplexed channels.

However, further slow down of the parallel channel keying rate may be accomplished by encoding more than one information bit upon one phase position. The four-phase position or quadraphase PSK modems are most commonly used over HF radio circuits. Since four-phase positions are available, two binary data bits may be encoded upon each phase position (see Figure 1).

	Two-Bit Binary Word			
	00	01	11	10
Tone Phase Position, degree	0	90	180	270

Figure 1 Quadraphase Encoding Technique

Because the PSK systems transmit the information in the amount of phase change between successive bits on each channel tone and not in the amount of frequency change as in FSK systems, orthogonal signalling techniques are applicable to the PSK systems. This results in closely packed channel tones with low interchannel crosstalk. In order to achieve orthogonality, the frequency increment between adjacent channel tones must be an integral multiple of the reciprocal of the demodulation integration interval. If the channel tones are spaced at higher multiples than normally required to achieve orthogonal signalling, additional protection against the effects of crosstalk and multipath may be gained. This is accomplished, however, at the sacrifice of bandwidth.

At the receiving terminal, a phase reference must be established in order to recover the binary data from the phase information. Two methods of obtaining the phase reference are employed---the time-differential technique and the frequency-differential technique.

The time-differential technique derives the phase reference for each of the parallel PSK channels from the phase-shift tones themselves; that is, the information content is determined by the amount of phase change encountered between consecutive symbols on each channel. Since the phase measurement or comparison is made over an information-bearing symbol interval, the technique is called time-differential phase-shift keying. While signals received over long-haul, ionospheric paths do encounter amounts of phase, frequency, and amplitude changes because of the media itself, the time-differential technique relies upon the received signal having a sufficiently high, short-term phase stability which must exist for most of the symbol interval.

In frequency-differential systems, the phase reference is obtained by transmitting many unkeyed CW tones throughout the baseband. Since the tones are unkeyed, the receiving terminal has many real-time phase references to use in recovering the information. While time-differential requires time stability of the media as far as phase is concerned, frequency-differential systems require a high correlation of phase over a narrow frequency band.

Because of the narrowness of this band of high phase correlation, the information-bearing channel tones must be more closely packed than in the time-differential systems. This is reflected by the very long signalling symbols required when orthogonal signalling is used.

At the receiving terminal, the reference and information-bearing tones are translated to a common processing frequency, where, using correlation detection techniques as in the time differential systems, the binary information is recovered.

MODEM DESCRIPTIONS

Since it was desired to compare the performance of the two developmental modems, DEFT and KATHRYN, it was decided to also operate an off-the-shelf modem as a standard of comparison. Therefore, a standard FSK modem was used, and for the second test the well-known KINEPLEX, built by the Collins Radio Co., was also tested. Descriptions of these modems in their full-scale versions are given below.

Northern Radio/Rixon (AN/FGC-61A/Sepath Type DD-1003) Combination

This combination was included in the evaluation tests since it employs the commonly used FSK modulation technique. Although not applicable to satisfying the requiremnts of the task because of a lack of bandwidth economy, this combination served as a standard of comparison since much performance data is available for comparison of systems employing the FSK technique (AN/FGC-29, -60 and -61A) and other modem systems used for data transmission via HF radio.

AN/FGC-61A Voice Frequency Telegraph Terminal

This equipment is normally used for the transmission of telegraph, teleprinter or telemetering signals over sixteen parallel, FSK channels. The maximum keying rate for each channel is 90 bits/second; however, during normal operational use the channel speed of 75 bits/second is employed, resulting in a total data handling capability of 1200 bits/second (16 channels x 75 bits/second/channel). Each transmitting channel consists of a frequency-shift tone keyer whose output is shifted either 42.5 cycles above or below the center frequency of the channel (giving an overall frequency shift of 85 cps), depending on the state of the input data The sixteen center frequencies of the channels are separated by 170 cps, beginning at 425 cps and ending at 2975 cps. Therefore, the baseband occupancy of the aggregate audio signal is about 2650 cps (a nominal voice bandwidth)

At the receiving terminal, the two audio aggregate signals from the HF receivers, when operating through the use of space diversity, are applied to bandpass filters which separate the desired channel from the aggregate. The diversity combination is performed on a switched controlled (selection) basis; i.e., after maximizing the difference between the two diversity paths, the diversity path with the highest signal level is selected as the discriminator input where the MARK-SPACE decision is made.

Rixon Type DD-1003 Simplex Multi-Channel Sepath System

The Rixon/Sepath equipment allows the utilization of existing frequency division multiplex equipment to achieve a capability for transmitting high-speed data in the presence of HF multipath. Sepath, by synchronously disassembling the high-speed data into a number of lower speed data streams, allows this data to be transmitted via the slow-speed FSK equipment. At the receiving terminal, Sepath reassembles the data into the original high-speed serial format.

The use of Sepath equipment with the AN/FGC-61A provides a capability of handling high-speed serial data streams. For example, if the serial data rate was 1200 bits/second as the Sepath input, the output data of the Sepath would be sixteen parallel data streams at 75 bits/second, which is compatible with the FGC-61A Bit timing synchronization between transmitter and receiver is obtained by comparing the transitions in the received data to a clock reference pulse. If a time discrepancy exists, a phase corrector shifts the phase of the receiver clock to ensure phase and frequency coincidence. Since the time delay is not the same for all parallel channels across the voice baseband, delay equalizers are incorporated within the Sepath equipment to adjust for coincidence of the data transitions from all channels.

General Dynamics/Electronics DEFT (SC-302)

This modem was designed specifically for high-speed, point-to-point data transmission and reception over HF radio circuits. Incorporated within the modem are techniques to combat selective fading and symbol delay-spread caused by multipath.

While classified as a PSK system, the DEFT system obtains phase reference information from many (22) continuous tones, spaced throughout the transmitted baseband. Therefore, unlike time-differential PSK systems, which derive the binary data content based upon phase difference decisions between adjacent symbols in time and at the same frequency, the DEFT technique chooses to use real-time phase information, necessary for correlation detection, based upon the high correlation of phase between closely spaced tones. DEFT is, therefore, identified as a frequency-differential PSK system.

At the transmitting terminal, the DEFT modem accepts the high-speed (3000 bits/second) serial bit stream and converts it to many (40) parallel, slow-speed (75 bits/second) bit streams. Each parallel information channel consists of two tones whose phases contain the information. The keying rates of the slow-speed bit streams are further reduced by encoding three serial bits into one information channel symbol. Therefore, the channel symbol rate is 25 symbols/second (baud). Figure 2 illustrates the DEFT encoding technique as applied to the sine and cosine phase positions of the two tones which make up an information channel. It should be noted that only eight of sixteen possible coding combinations are used. Actually, four bits could be encoded at a sacrifice of approximately 2 db in signal-to-noise (S/N) performance.

In order to incorporate the advantages of orthogonal signalling, the information tones are separated by 25 cps. The 22 phase reference tones are spaced at 125-cps increments throughout the baseband, and between each reference tone are two information tone pairs. In order to determine course bit synchronization, two tones, 25 cps from reference tones, are transmitted near each end of the baseband, and since none of the tones are keyed, the 25-cycle separation allows resolution of bit timing (40 milliseconds = 1/25 cps) from the crossovers. The 125-cycle spacing between adjacent phase reference tones enables fine grain time correction from the crossover information. Although there

	Three-Bit Binary Word							
	000	001	010	011	100	101	110	111
Tone 1	+S +C	-S +C	+S +C	-S -C	+S -C	-S -C	+S -C	-S -C
Tone 2	+S +C	-S +C	-S -C	+S -C	-S +C	+S +C	+S -C	-S -C

Figure 2 DEFT Encoding Technique

are twenty-one 125-cycle slots, each of which contains two data tone pairs,two of these tone pair positions are occupied by sync tones. Therefore, there are 40 data tone pairs for information transmission. The 22 phase reference tones, which are transmitted together with the 40 data tone pairs to attain a 3000-bit/second capability, occupy 2625 cycles of bandwidth (375 to 3000 ~).

At the receiving terminal, all received tones are translated to a common processing frequency. "Coherent" detection is accomplished by cross-correlating the received signal with locally generated models of each of the signalling symbol possibilities (see Figure 2). All the correlator outputs are weighted in a resistor matrix so as to match the weighting of the transmitted signal elements, and then the decision on received symbol is made on a "maximum likelihood" basis, i.e., the largest correlator output is selected as the transmitted symbol.

When diversity reception is available, post-detection combining, employing the equal-gain method, is used. With this method, the stronger signal dominates in the final decision process.

In order to combat frequency selective fading, DEFT employs a segmented AGC technique which requires that the received signal be passed through a number of narrow band bandpass filters whose average outputs are maintained relatively constant. In this manner, the effects of the narrow attenuation notch passing through the baseband are reduced.

Another propagation anomaly which DEFT is designed to combat is multipath delay-spread. By virtue of the long transmitted symbol compared to the prevailing multipath delay, the intersymbol interference is minimized.

Collins Radio KINEPLEX (TE-202)

KINEPLEX is a well-known time-differential PSK modem. The TE-202 model is a four-phase system which phase-multiplexes two bits of information on each of twenty tones. Each tone is keyed at a 75 baud; thus, the aggregate data rate is 3000 bits/second.

The detection process is a synchronous technique, employing integrate, sample, and phase-detection operations. The incoming signal is integrated in a gated, high-Q, mechanical (Kinematic) filter. Positive feedback is employed to make the effective filter Q-infinite. Gating is synchronous with transitions in the baud, and while the gate is open, the energy in the filter builds up in a linear fashion. When the gate is closed, the filter continues to ring with a constant amplitude and phase. Two such filters are used, each integrating a single channel on alternate frames. A filter is sampled immediately after the input gate is turned off and, again, one frame length later, after which it is quenched. The sample is compared with the phase reference from the previous frame and the two bits of information are extracted. The filter is allowed to ring to provide the phase reference for the following frame, while the filter which contained the previous ringing reference is quenched and accepts the new symbol for integration.

Phase positions of 45, 135, 225, and 315 degrees with respect to the references are used. Resolution of the rectangular components of these phase vectors yields polarity information for two bits/position. These components are obtained by mixing the signal sample directly with the reference sample and with the reference after it has been phase-shifted by 90 degrees. One phase comparison yields the sign of the rectangular components on the same axis as the reference, while another comparison determines the sign of the component on the orthogonal axis. Receiver synchronization is accomplished by comparing the phase of a tone located at 2915 cps with a transmitted tone and correcting the fundamental timing signal generated in the receiver synthesizer. Crosstalk is minimized by spacing the channels at frequencies which are integral multiples of the integration time, i.e., 110 cps for 9.1-msec integration.

General Atronics Simulated Extended Rate KATHRYN

A full-scale version of the Simulated Extended Rate KATHRYN Modem (Model S-3000X Tested) would be a quadraphase, time/frequency differential coherent PSK system. In a 3000-bit/second configuration, the Extended Rate KATHRYN Modem consists of 42 parallel channels (two of which are employed for synchronization). The 40 information channels transmit 50 symbols/second, and since three information bits are transmitted during two successive channel symbols, the total data rate of 3000 bits/second is achieved. As this system also incorporates orthogonal signalling techniques, a time guard band of 6.6 ms is available. Several advanced signal processing techniques are used, including:

(a) Frequency-division multiplexing employing unique circulating delay line (Fourier transformer) methods.

(b) Updated stored phase reference obtained from flanking and co-channel phase contributions of the previous time frame. A "smoothed" reference is averaged by successive frame integration.

(c) Post-decision feedback to separate phase reference information from information-bearing components when single bit time differential techniques are used to update the stored reference.

(d) Pseudo-random sequence synchronization achieved by cross-correlation on pilot sequence.

At the transmit terminal, the input serial data stream is converted to short bursts of phase-shifted RF carrier. Serial-to-parallel conversion and frequency-division multiplexing are achieved by employing an analog recirculating delay line (Fourier transformer), which converts the stream of short RF bursts into a set of parallel phase-keyed tones. Two pseudo-random sequences are used in the system. One sequence is mixed with the serial data stream to make up the information channel which ensures changes in the data level; i.e., for a continuous input state (MARK or SPACE), crossovers are ensured for timing recovery purposes. The other pseudo-random sequence is applied to the pilot component of the phase-quadrature signal so that, at the receiving terminal, the phase reference information can be extracted because of _a priori_ knowledge of the pilot sequence modulation.

At the receiving terminal, the parallel frequency-division multiplexed channels are inserted into another circulating delay line (inverse Fourier transformer), where parallel channels are converted into a serial stream of short bursts of phase-modulated RF carrier. After phase and amplitude weighting from a digital storage "bookkeeping" system, the serial data bits are obtained by correlation detection techniques, and the corresponding phase references for each bit (channel) are updated. The unit associated with this matched filter technique is designated as the F-Rake Section of the receiver (demodulator). Also provided within the system are an automatic frequency control loop (for Doppler frequency shift control), and an automatic phase control loop (for circulating delay line control).

KATHRYN Encoding Technique

At the transmitting terminal, the PSK signals are encoded such that one quadrature phase component contains data information (I) during all transmitted symbols, while the other quadrature component alternately contains data information (I) and phase reference sequence information (P). This technique is illustrated in Figure 3. The procedure is then alternated in the flanking frequency channels so that when one channel is transmitting an IP symbol, for example, the flanking channels will be transmitting II symbols as indicated in Figure 4.

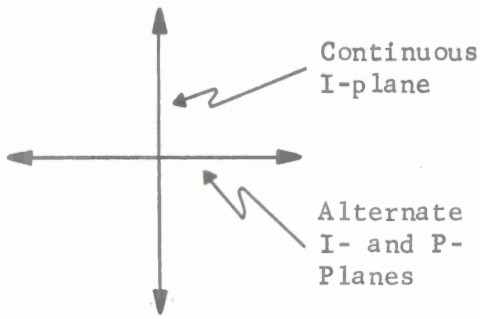

Figure 3 KATHRYN Encoding Technique

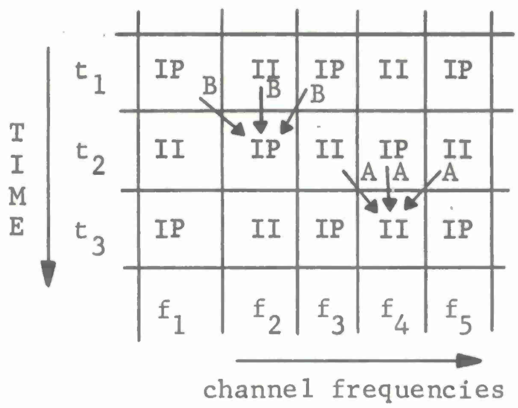

Figure 4 KATHRYN Phase Reference Extraction

KATHRYN Phase Reference Extraction

Because of the temporal changes in the propagation media, two methods of developing a phase reference for correlation detection purposes are employed in this system. If the time variation of the media is slight, a phase reference may be obtained by integrating the phase of the received signal over several symbol periods, and since the information-bearing (I) quadrature components are modulated by a pseudo-random sequence, their effect on the reference phase should be effectively eliminated when the signal is integrated over several symbol periods.

The resultant phase reference is an average or "cleaned-up" stored reference for use in the demodulation of all of the received symbols (both II and IP symbols).

When the media is rapidly time-varying, the stored reference technique is invalid, and time-differential phase reference is obtained from the previous symbol frame only. Because of the characteristics of the KATHRYN encoding technique, this phase reference is obtained by two similar methods.

In order to demodulate an all-information (II) symbol, the phase reference is derived from three sources (arrows marked A in Figure 4); namely, the phase reference component of the previous IP symbol in the same channel and the phase information obtained from the previous II symbols in the flanking channels. These three sources then are used to create the phase reference for detection of an II symbol.

For demodulation of an IP symbol, the phase reference is also developed from three sources (arrows marked B in Figure 4). In this case, the phase reference is derived from the previous II symbol in the same channel and from the phase information obtained from the previous IP symbols in the flanking channels.

While the P-component of the received IP symbols is known because of *a priori* knowledge of the pseudo-random sequence modulation, the information-bearing I-component must be removed in order to extract the reference updating information. This is accomplished by a technique called "post-decision feedback," which is also applied to deriving phase reference updating information from II symbols.

Post-decision feedback functions in the following manner. After the binary data content of the received symbol has been detected (using a phase reference derived during the previous symbol frame), the complementary vector of the binary decision made in the all-information plane is added to the symbol vector, which cancels the all-information component and leaves only the P-component for received IP symbols and an I-component for received II symbols. Since the pseudo-random sequence which modulates the P-component is known by *a priori* knowledge, this component can then be readily used as a contributing source in deriving the phase reference for the succeeding symbol. When the received symbol is all-information (II), the remaining component, after post-decision feedback, is, therefore, either in-phase or 180 degrees out-of-phase with the phase reference, and can also be used as a contributing source. Since three sources are employed to create the phase reference, the effect of incorrect binary decisions is minimized

SECTION III

TEST CONFIGURATION

TEST CIRCUIT

Ideally, one would like to test the newly developed techniques in the laboratory by simulating the characteristics of the transmission medium which the techniques have been designed to counter or tolerate. This method of approach is feasible when all of the pertinent characteristics of the medium to be simulated are known to a sufficient degree. Also, even when the media characteristics are known, the problem of an accurate simulation facility is still present since the numerous variables of the ionosphere must all be accounted for in the simulation. Data involving the characteristics of long-haul HF radio paths are scanty, especially on paths which are long-haul, transequatorial and oblique azimuth in nature. Therefore, it was deemed necessary to conduct a field test over the exact ionospheric path on which the equipment will ultimately be used or a path very similar geographically.

Originally, consideration was given to a test path over a radio circuit between Cape Kennedy and Ascension Island (one of the circuits which would ultimately employ the modems for data transmission). However, investigation disclosed that the circuit would be available for test purposes on a noninterference basis only. Since this would necessitate interruption of the testing any time administrative or test program traffic became necessary, it was felt that for economy of time and money, it was more desirable to lease a commercial circuit which closely resembled the Eastern Test Range (ETR) circuit.

A survey of available commercial facilities determined that a radio circuit existed between Riverhead, Long Island, N. Y., and Pretoria, Republic of South Africa. This circuit is shown in Figure 5, together with the operational circuits of the ETR. The considerable dependence of the ETR upon HF radio in the down-range areas, not only for point-to-point communications but also for ship-to-shore and aircraft-to-ground communications, should be noted. It can be seen that the 6900-nautical mile (n.m.) test circuit closely parallels the existing operational ETR circuits.

The transmitting terminal is located at Olifantsfontein, Republic of

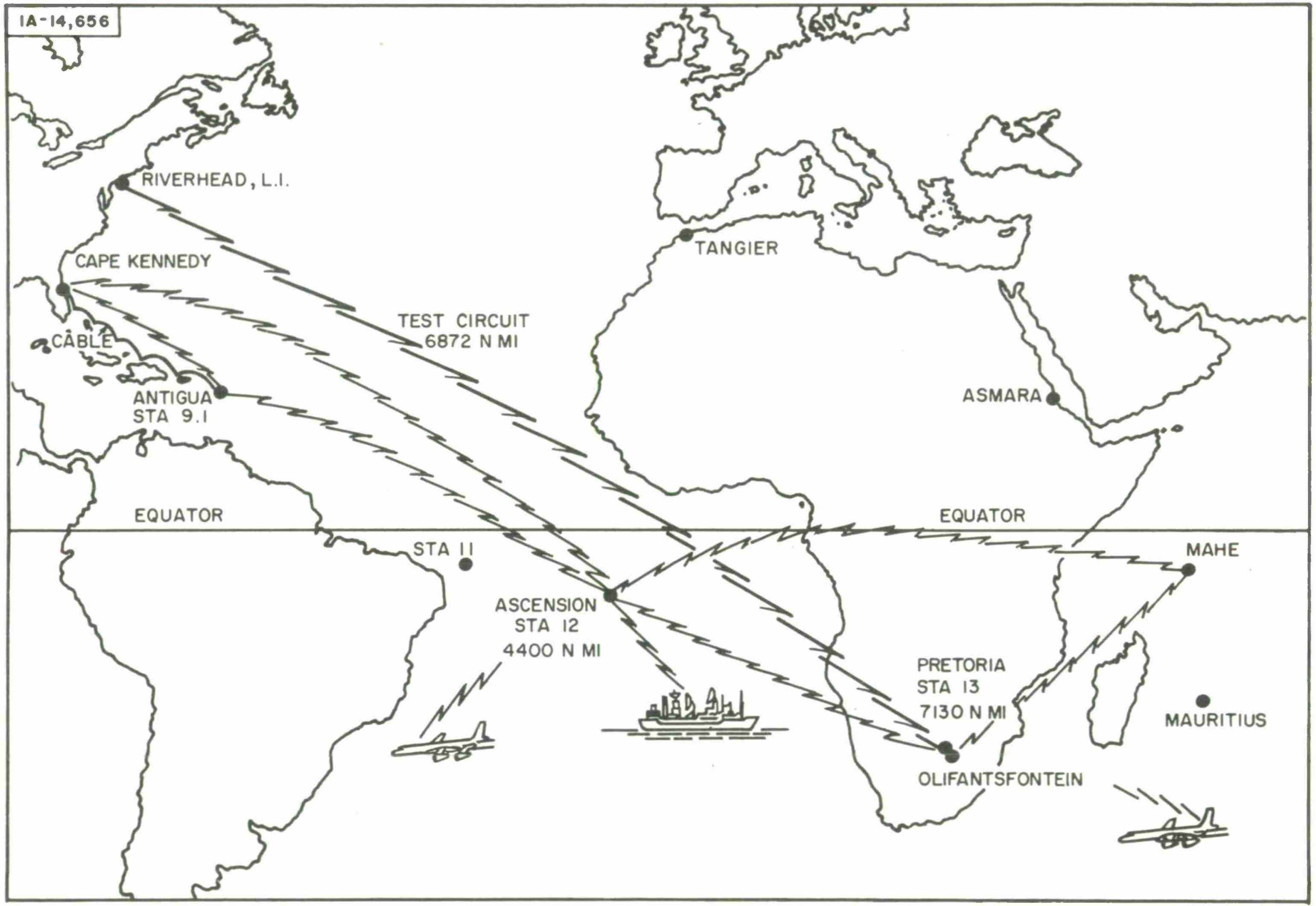

Figure 5 ETR Circuits

South Africa, about 17 miles south of Pretoria, and is owned and operated by the South African Ministry of Posts and Telegraphs. The receiving terminal, located just outside of Riverhead, Long Island, N.Y., is owned and operated by the Radio Corporation of America Communications (RCAC) division. After being informed of the evaluation test program, the South African Government agreed to lease the transmitting channel at a nominal fee, and RCAC agreed to lease the receiving antennas and equipment space at their Riverhead, Long Island, facility.

The radio circuit, from Olifantsfontein (25° 58' S Latitude, 28° 14' E Longitude) to Riverhead, N. Y., (40° 55' N Latitude, 72° 40' W Longitude) covered a great circle path of approximately 7913 statue miles, transversing about 65 degrees of latitude and 100 degrees of longitude.

FREQUENCY UTILIZATION

HF radio communications utilize the frequency range from 2 to 30 mc. From the list of radio frequencies assigned to the South African Post Office radio station, ZUD, nine frequencies were made available to MITRE solely for test purposes. As indicated in Table I, the spacing between the available frequencies was such that good spectrum coverage was provided.

Table I

Frequencies Assigned to Radio Station ZUD
Olifantsfontein, Republic of South Africa

ZUD Station Call	Frequency (kc)
21	6,950.0
23	7,595.0
73	9,048.0
75	10,350.0
76	10,565.0
77	13,366.5
79	16,215.0
82	18,892.5
85	20,945.0

The selection of test frequencies within the 7- to 21-megacycle range is substantiated by both the South African Post Office and RCA Communications optimum working frequency (OWF) predictions for the two test periods (Figures 6 and 7). While not strictly adhered to, the predictions did serve as estimates of proper operating frequency. Because of daily and even hourly variations in the propagation path, the receiving site initiated all requests for frequency change by continuous monitoring of the usable frequencies. The monitoring was conducted by the RCAC personnel.

When available, a second transmitter, transmitting two CW tones on the next usable radio frequency, was provided by the South African station so that the RCA personnel at the receiving site could monitor not only the quality (amount of interference and noise), but also the strength of the signal.

Because the audio baseband frequency allocation of each assigned carrier frequency varies between 3 and 12 kilocycles, the South African Post Office personnel made available their assigned frequencies with basebands at least 6 kilocycles wide. The emission of the transmitters

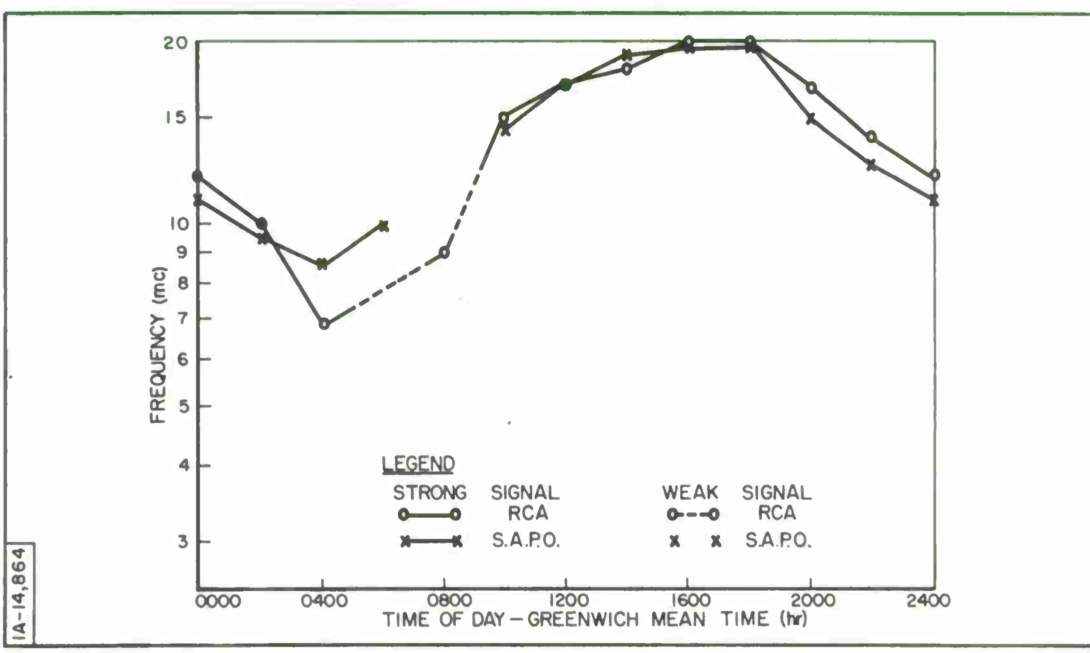

Figure 6 OWF Predictions, Johannesburg - New York, April 1964

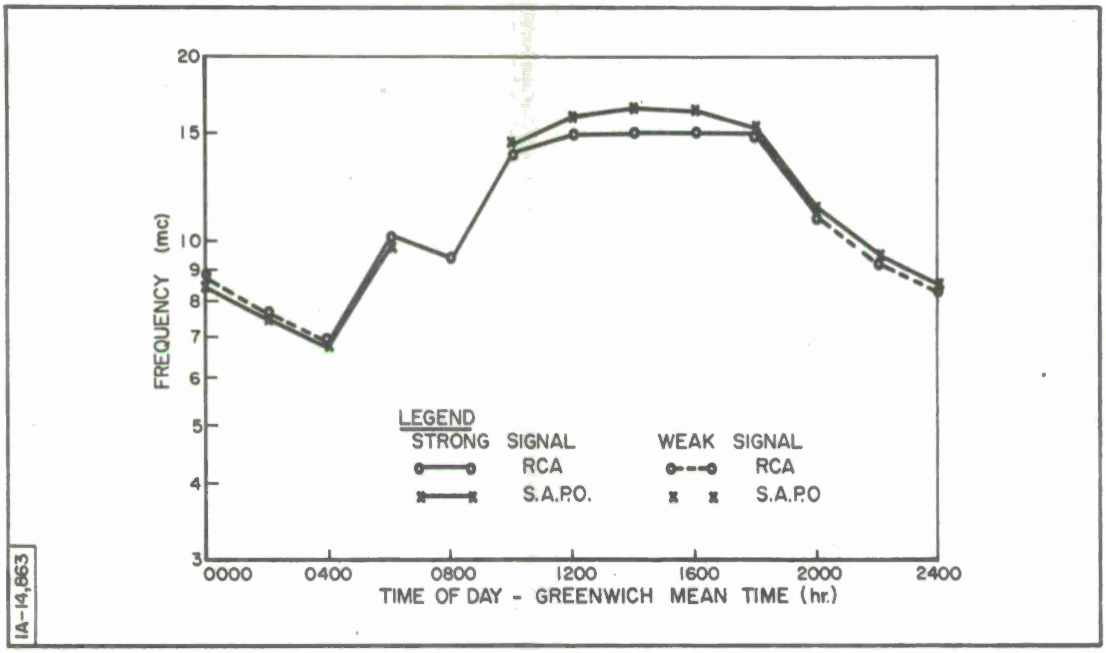

Figure 7 OWF Predictions, Johannesburg - New York, July 1964

was a suppressed-carrier, independent single-sideband (ISSB) signal, with a maximum of 12-kilocycles bandwidth consisting of four independent 3-kilocycle basebands or slots as shown in Figure 8. Therefore, when the allocation was 6 kilocycles, each modem was tested sequentially in time within one 3-kilocycle voice inboard slot, while the duplex teletype order wire signal was transmitted in the other 3-kilocycle inboard slot. This type of test operation was called the single mode of operation. When 9- and 12-kilocycle allocations were available, it was possible to test two modems simultaneously by transmitting the audio signals of the modems in the two inboard slots adjacent to the carrier. This testing was called the dual (or parallel) mode of operation, and during these periods the order wire signal was translated in frequency by a frequency multiplexer unit and transmitted in either the upper or lower outboard 3-kilocycle slot. Figure 8 illustrates the transmitter emission during a typical "dual or parallel" test run.

Although the baseband frequency assignment was a factor in selecting the test mode of operation, the density of the co-channel interference (QRM) within the baseband was the dominant factor. At the receiving site, the RCA personnel constantly monitored the operating frequencies and informed the transmitter site of slight carrier frequency movements which would minimize the amount of QRM encountered.

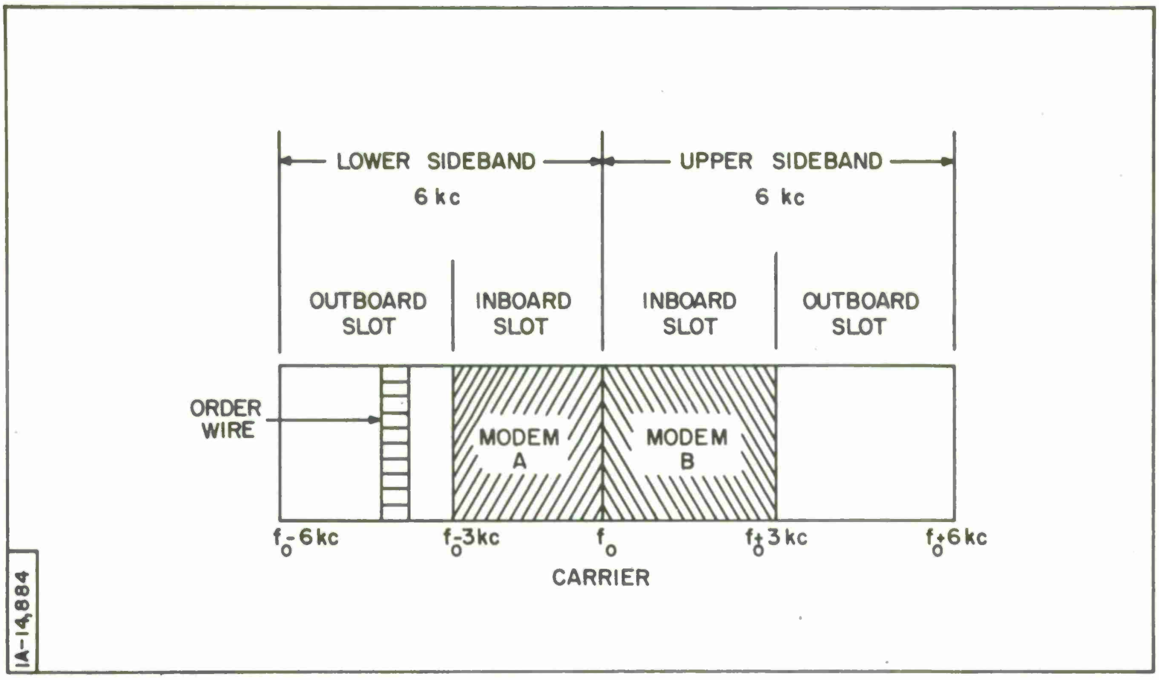

Figure 8 12-kc ISSB Baseband Allocation

Since the frequencies were commercial allocations, and possibly not as QRM-free as military allocations might be, this method maximized the amount of testing possible in both the single and dual modes of operation and minimized the amount of data editing required during the data reduction process.

TEST DATA MEASUREMENTS

The primary purpose of the test program, as previously indicated, was to obtain data on the error performance of the modems being tested. However, because of the perturbations and variations characteristic of transmission via a multihop ionospheric path, the test measurements included not only those necessary to obtain the statistical error performance of the modems tested, but also measurements of the transmission path characteristics in order to substantiate to the statistical information.

With some propagation media it is possible to make periodic measurements on nearby frequencies and predict the results that should be obtained, since the path characteristics do not vary substantially over the time periods and frequency separations used. However, in testing over a long-haul, HF radio path, the path varies rapidly in time and with frequency because of the phenomena of the medium itself and from man-made sources. Therefore, to obtain a qualitative estimate of the actual channel characteristics, it was necessary to continuously monitor and record data on the channel performance. When possible, deleterious effects, present in the channel, were avoided by utilizing a better frequency. However, the received audio was continuously recorded so that as many effects as possible could be categorized and accounted for during the data analysis period.

Primary Test Data

Digital circuitry and associated electronic and electromechanical counters were used to obtain the statistical error data utilized in determining the system performance of the test modems. This data for each test run was recorded on:

(a) A Consolidated Data Sheet (see Figure 9), which was used to record the cumulative error count for the run as indicated on the Beckman electronic counter, as well as information regarding the RF carrier frequency, data rate, test pattern, etc. The readout of the electromechanical counters of the Error Distribution Analyzer (EDA) were also recorded. Space was also available below the EDA readings from computations of the run bit error rate (BER).

(b) A Beckman paper tape printout which provided the cumulative error count at 1-minute intervals for the duration of the test run. This tape was attached to the Consolidated Data Sheet in the space provided.

(c) Tape recordings of the sequential errors detected by the error recognition matrix (ERM) as supplied to the electronic counters and the EDA. Bit timing was also recorded on a second channel on these tapes.

Collateral Environmental Data

Collateral data on the characteristics of the propagation medium were also recorded. Real-time monitoring was provided visually (by two

H. F. RADIO – DIGITAL DATA TRANSMISSION TESTS DATA SHEET
RECEIVING TERMINAL – RIVERHEAD, LONG ISLAND N. Y.

Run # ________ Modem ________ single _____ dual _____ Date ____________________ 1964

R. F. Freq. ________ kc Data Rate ________ b/sec Test Pattern ________________ Word

Sideband

LSB ______ USB ________

AGC Connection

________ ________

Multipath Spread

Min / Ave / Max

______ ______ ______ millisec

Tape Recorder Footage

	Start	End
2 ch. audio	______	______
2 ch. EDA	______	______
7 ch.	______	______

Error Count ______________

Sync Errors ______________

____

Test Engineer

EDA RECORD

1	2/3	4/7	8/15	16/31
○○○○○ 1 2 4 8 16	○○○○ 1 2 4 8	○○○ 1 2 4	○○ 1 2	○ 1
1 [ ] x32	2 [ ] x16	3 [ ] x8	4 [ ] x4	5 [ ] x2
6 [ ]	7 [ ]	8 [ ]	9 [ ]	10 [ ]
11 [ ]	12 [ ]	13 [ ]	14 [ ]	15 [ ]
16 [ ]	17 [ ]	18 [ ]	19 [ ]	20 [ ]

SIGNAL STRENGTH

	Signal	Noise	Ratio
Rec #1	______	______	______
Rec #2	______	______	______

End Time ____________

Start Time ____________

Run Length ____________

Total Bits ____________

$\frac{\text{Error Count}}{\text{Total Bits}}$ = Error Rate

________ = ________

(STAPLE BECKMAN PRINTOUT TAPE HERE)

↑

DEM RECORD

Figure 9 Sample Test Data Sheet

spectrum analyzers) and audibly (by loudspeakers) so that, in the event of channel degradation, a frequency transfer could be affected (if possible) or, in any case, an entry could be made in the station log noting the circumstances.

The history of the channel, for post-test analysis purposes, was obtained by recording the received audio signals on magnetic tape and also by recording a measure of the signal and noise strengths on chart paper with a pen recorder.

TRANSMITTING SITE TEST CONFIGURATION

The transmitting terminal was installed in the low-power apparatus room at the Olifantsfontein transmitter site, adjacent to the South African exciters. The equipment included the KATHRYN modem (two racks); MITRE equipment, including word generators and a patch panel (one rack); Northern Radio (N. R.) Tone Keyers (one rack); the DEFT modem (one rack); and teletype order wire send/receive equipment. During the June/July tests, the KINEPLEX modem rack was located adjacent to the DEFT modem rack.

MITRE personnel operated the modem test configuration at both the transmitting and receiving terminals. Maintenance on the DEFT, KATHRYN, and KINEPLEX modems was accomplished by contractor representatives.

Modem Test Configuration

The modem test configuration at the transmitter site is illustrated in Figure 10. The test equipment used with the modems consisted primarily of pattern (or word) generators and miscellaneous measuring instruments. The word generators supplied the modems with a 52-bit binary data sequence, 16 bits of which were used for pattern synchronization purposes. Bit timing for the word generators was derived from the timing clocks in the modems.

In order to evaluate the performance of each system on an equal energy per bit basis, the available transmitter power was maintained constant while the audio output level of each modem (drive) was set in accordance with the values computed in the Appendix. A Ballantine Modem 320 True RMS Voltmeter was used for setting each modem audio output level. Oscilloscopes and electronic counters provided test equipment for trouble-shooting and maintenance purposes.

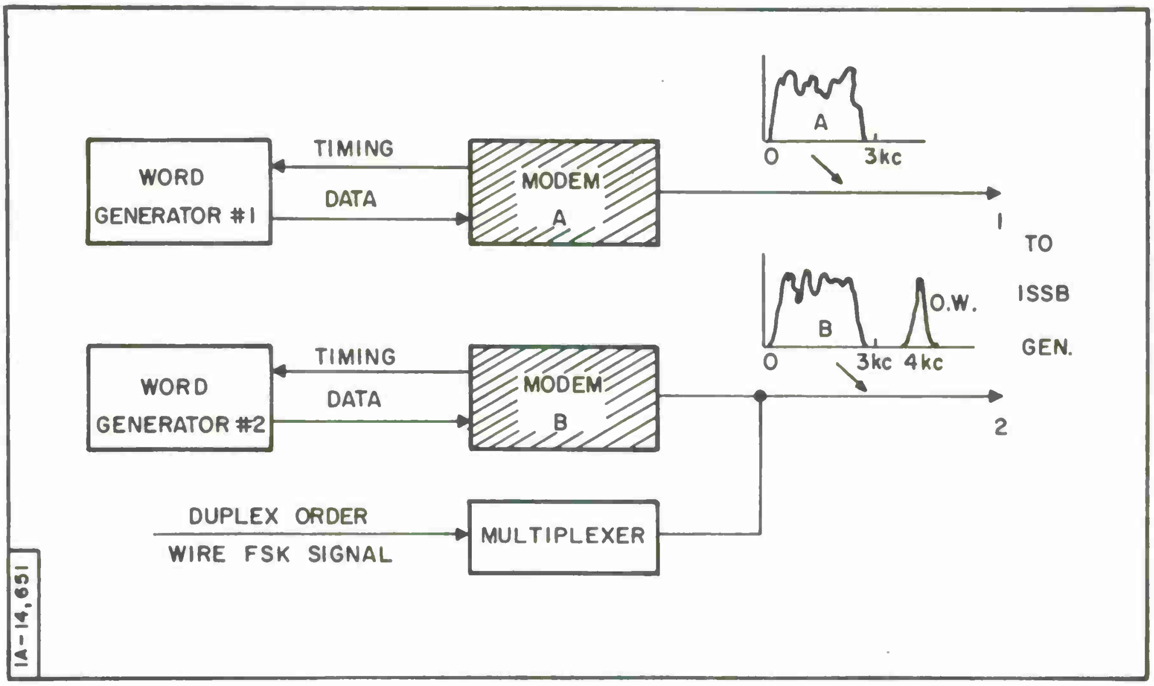

Figure 10 Transmitter Site Modem Test Configuration

Radio and Teletype Equipment

The audio outputs of the modems under test were patched into an independent SSB generator (Marconi Model SSD2A), which transformed them into two independent, SSB voice bandwidth signals on each side of a low-level, RF carrier. These signals were used to drive the high-power linear amplifier in the transmitter.

The linear amplifier (or transmitter), Model STC-DS 13, manufactured by Standard Telephone and Cable of England, was rated at 40 kilowatts peak envelope power (PEP). Its output was fed to a stacked-element, interlaced rhombic antenna configuration. In order to ensure frequency stability, the transmitter frequencies were derived from a frequency synthesizer (STC Type A1426). A 100-kilocycle signal with a stability of 1 part in 10^8 per day was obtained from the crystal standard in a Collins Radio high-power amplifier (owned by the ETR), and served as the basic frequency standard of the synthesizer.

The full duplex order wire equipment at the transmitter site consisted of a teletype keyboard/perforator and a transmitter-distributor (with associated page printer) for outgoing messages and a page printer for incoming messages. The outgoing order wire traffic was transmitted on the same carrier as the modem signals, which necessitated the use of a multiplexer (N. R. Model 248) for translating the order wire during dual operation.

RECEIVING SITE TEST CONFIGURATION

The receiving site equipment layout at Riverhead, Long Island, included an Ampex FR-100 7-channel tape recorder, send and receive teletype machines, a table for data recording and tape recorders, the modems described above, four racks of receiving and data measuring equipment, and a KATHRYN modem. The functional block diagram (Figure 11), indicates the interconnection between the receivers, modems and data collecting equipment.

Receiving Equipment

The test signals were received in space diversity by two rhombic antennas (leased from RCA), oriented toward the transmitting site. These antennas fed a stabilized receiving system consisting of two R-390 A/URR HF communications receivers and two SSB converters (Model CV-157). The Manson SBM-1 (390A) Sideband Conversion Kit provided the stable frequencies for both the receivers and converters. The audio outputs from the converters were patched into the digital data modem receivers for diversity combination and detection purposes.

Data Measurement Instrumentation

The data measurement equipment can be divided into four functional categories:

(a) Statistical data analysis equipment, consisting of

(1) The Digital Error Measuring (DEM) equipment,

(2) The Error Distribution Analyzer (EDA),

(3) A timing and error recorder;

(b) Collateral environmental analysis equipment, consisting of

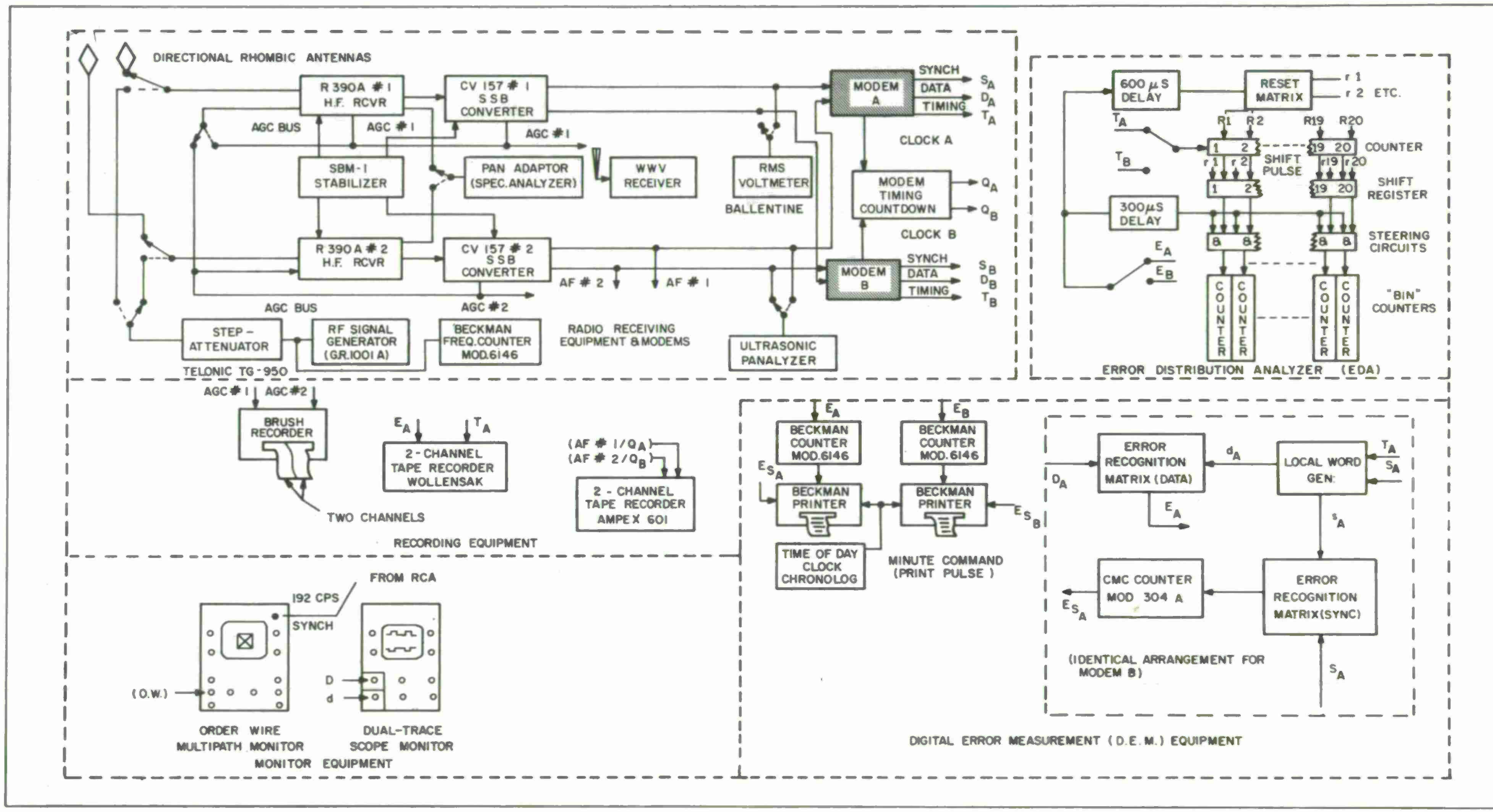

Figure 11 Receiving Site Instrumentation (Riverhead, N. Y.)

(1) Signal strength recorder,

(2) Radio interference monitor,

(3) Received audio aggregate signal recorder,

(4) Multipath monitor;

(c) Auxiliary test equipment, consisting of

(1) Duplex teletype order wire,

(2) Calibration equipment,

(3) Frame synchronization monitor,

(4) Audio level monitor;

(d) Backup equipment, consisting of

(1) Receiving equipment, and

(2) Magnetic tape recorder.

Statistical Data Analysis Equipment

This equipment provided a means of measuring and collecting system errors for deriving statistical analysis of the systems from both a cumulative (coarse) and time-distributive (fine-grained) standpoint. The DEM equipment recognized sync and data errors and provided a minute-by-minute progressive summation. The EDA provided, as an output, a coarse cumulative distribution of the number of good bits between errors while a magnetic tape recorder was used to collect the time distribution of errors on a fine-grained basis.

DEM Equipment. The DEM equipment consisted of two error recognition matrices, two totalizing counters, and a word-generator. The occurrence of an error in the serial data stream was recognized by a logic circuit (a half-adder circuit). In the same manner, the occurrence of only a false sync pulse (not the lack of sync pulse) was recognized. The outputs of both error recognition matrices were totalized in individual electronic counters, and a cumulative total of both types of errors was printed on paper tape every minute upon command from a clock. An identical DEM capability was provided for periods of dual operation.

EDA. The EDA was used to provide data indicating the statistical frequency distribution of the number of good bits received between errors. This equipment consists of a number of electronic and electromechanical counters which measure, on a cumulative basis, the number of times during each test run that k good data bits were received between errors. The limits of k are given by:

$$\{2^n - 1\} \leq k \leq \{\sum_1^n 2^n\},$$

where n is the level of the counter.

For example, if, at the end of a test run, the fourth electromechanical counter ($n = 3$), shown in Figure 9, indicated a count of 9, it meant that 36 (9 x 4) periods occurred during which between 7 and 14 good data bits were received between errors. As another example, if the first counter ($n = 0$) indicated a count of 12, it meant that 384 (12 x 32) periods occurred during which no good data bits were contained between errors. While the EDA does not reveal the exact time distribution of these consecutive errors (bursts), some measuremnt of the average burst length can be obtained.

Timing and Error Recorder. A two-channel, magnetic tape recorder was used to record both the serial bit timing and the output from the error recognition matrix. This equipment was used in conjunction with the EDA. The data recorded on the tape, when reduced, will provide a fine-grained, time distribution of errors.

Collateral Environmental Analysis Equipment

This equipment was used to assess the quality of the transmission channels in order to provide editing information during the data reduction process.

Signal Strength Recorder. A continuous recording of the signal strength from both diversity receivers was made during each test run. The AGC voltages from the receivers provided the signals for the Brush Mark II Two-Channel Pen Recorder. By comparing the AGC level during the test run with the level when the transmitted signal was removed, a measure of the received signal-plus-noise to noise (S + N)/N ratio was available.

Radio Interference Monitor. Two spectrum analyzers were used simultaneously during the tests. One analyzer, whose operating frequency was the intermediate frequency (IF) of the receiver, monitored the interference in both 3-kilocycle slots adjacent to the carrier. The other analyzer, an audio frequency type, was switched to either sideband in order to observe more details of the interference characteristics.

Received Audio Aggregate Signal Recorder. For post-test data reduction and editing purposes, a two-channel magnetic tape recorder was used to record the audio aggregate signals during every test run. Under single-modem operation conditions each channel recorded one of the diversity signals, while under dual operating conditions only one received audio signal for each modem was recorded (no diversity information).

Multipath Monitor. Periodic monitoring of the shifting of the crossovers in the order wire ARQ signal received from South Africa was employed as a coarse estimate of the amount of multipath spread encountered on the circuit. An oscilloscope presentation was obtained by using the order wire aggregate signal and ARQ timing to generate a visual display of the multipath spread, which was recorded in the station log.

Auxiliary Equipment

This equipment was used to ensure proper equipment operation and also provided teletype communication between the circuit terminals.

Duplex Teletype Order Wire. The teletype equipment at the receiving terminal was provided by RCA Communications. It consisted of a receive teleprinter and a send keyboard/printer (50 baud). This teletype link was used to advise the transmitter terminal of frequency changes (ZAL), test modem substitutions, and also to handle administrative traffic. As described above, the signal also provided a source of multipath spread information.

Peripheral Equipment. This equipment included that used to calibrate the radio receivers, chart recorders, and spectrum analyzers, and also the monitoring equipment to assure proper frame synchronization and modem audio output levels.

Backup Instrumentation

This equipment was available in the event of failure of the receiving system or data acquisition system. A spare R-390A/URR radio receiver and a CV-157 SSB converter were available for use if the primary system failed and, in addition, RCA receiving equipment, although unstabilized, was made available to MITRE. An Ampex FR-100 magnetic tape recorder, although not required during the tests, was outfitted so that it would replace the primary test instrumentation in the event of a system failure by recording the following on seven channels:

(a) recorder speed control information,

(b) voice commentary and time of day information,

(c) signal strength (AGC) of both receivers (two tracks),

(d) audio aggregate signals from each receiver in diversity and a basic modem timing signal (two tracks), and

(e) the teletype order wire demodulated signal.

TEST MODEM CONFIGURATION

The modems evaluated during these tests were scaled versions of designs that would be capable of transmitting 3000 bits/second in a 3-kc bandwidth. In order to limit procurement costs, the Electronic Systems Division directed that the feasibility demonstration modems be delivered with a data handling capability limited to 750 bits/second. They did, however, incorporate all the design techniques that would be employed in a full-scale model.

The 750 bit/second rate, of course, is not consistent with the proposed C.I.T.T.* criteria for a family of standard bit rates defined by:

$$\text{Bit rate} = 75 \times 2^n \quad (n = 1, 2, 3 \ldots).$$

As a consequence, the bit rates for the leased modem systems (KINEPLEX and N. R.) were not identical to the developmental models or to each other. The nearest bit rate to 750 bits/second in the case of KINEPLEX was 1200 bits/second, and for the N. R./Rixon combination, the bit rate used was 900 bits/second. The following paragraphs describe the modem configurations as they were tested.

N. R./Rixon FSK Modem

The N. R. modem is standard 16-channel FSK equipment. Because of the scaled bit rate, only 12 channels were used to transmit the test data. The other 4 channels were continuous tones to minimize the energy per bit differential that existed between this modem and the others tested. By adjusting the bit timing of the Rixon equipment, 900-bit/second operation was obtained, which converted the 900-bit/second serial data into twelve 75-bit/second parallel channels, compatible with the FSK equipment. Figure 12 depicts the baseband spectrum of the modem during the tests.

Collins KINEPLEX Modem

Although the TE-202 modem had a 2400-bit/second capability, the modem was operated at 1200 bits/second during the test. Of the 16 parallel tones, only 8 had to be keyed to attain the 1200-bit/second rate. The remaining 8 tones were also transmitted (unkeyed) to decrease the bit energy differential, as in the FSK modem case. This resulted in a decrease of the actual peak power level so that the peak-to-average power ratio was more realistic. The spectrum of the KINEPLEX modem, as tested, is illustrated in Figure 12.

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*Consultive Committee on Telephone and Telegraph.

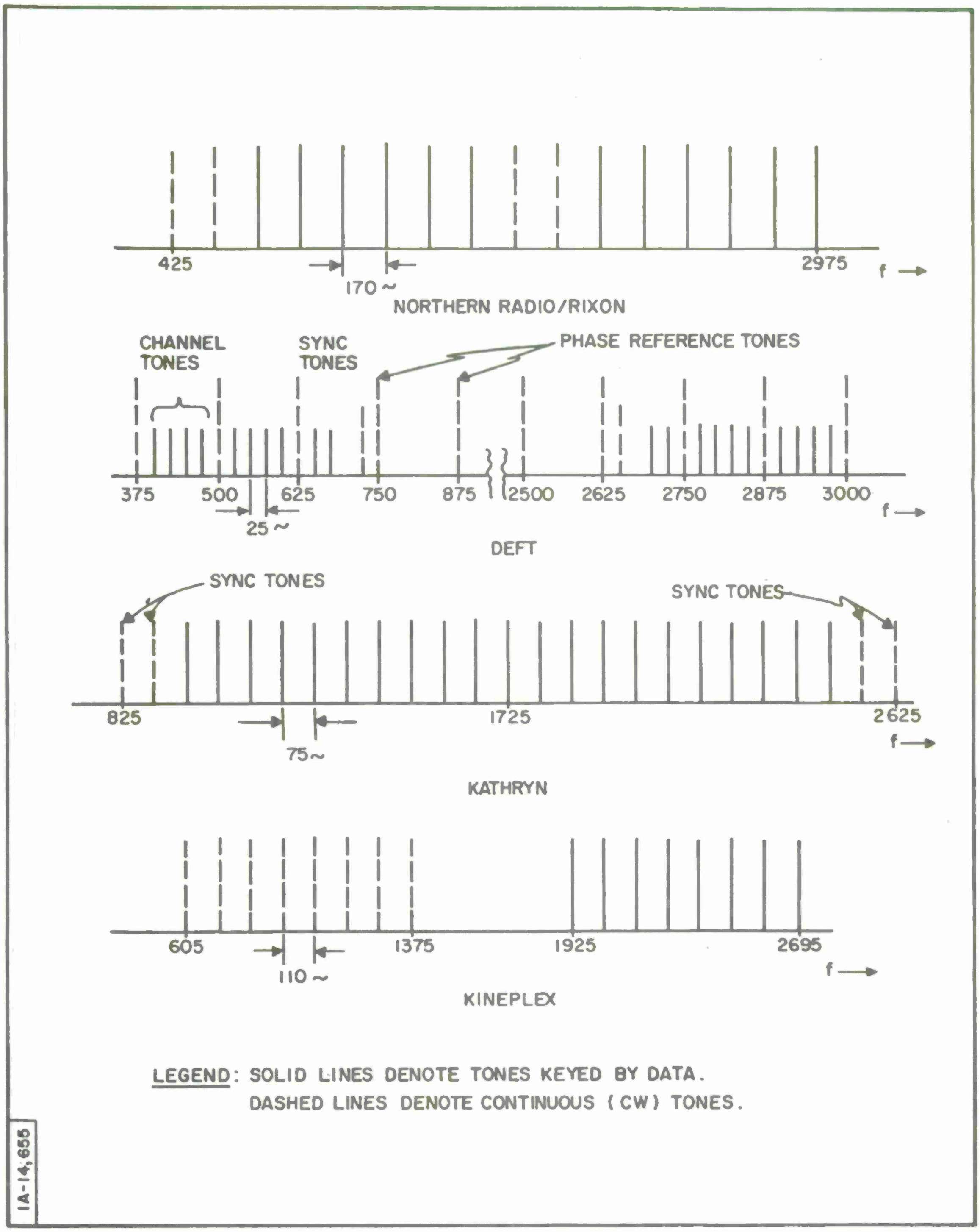

Figure 12 Tested Modem Baseband Spectra

Simulated Extended Rate KATHRYN Modem (Model S-3000X)

The KATHRYN modem tested operated at 750 bits/second. However, this prototype modem incorporated all of the techniques utilized in a full-scale (3000-bit/second) modem. Since it was a scaled version, it consisted of only 24 parallel channels. Twenty channels were used for transmitting data, 2 channels were used to synchronize the system pseudo-random sequence, and 2 channels were transmitted (unkeyed) to minimize the energy per bit differential between the systems. The baseband of the system, as tested, is shown in Figure 12.

The channel-signalling rate of the full-scale system would be 50 symbols/second. In the model tested, the signalling rate was 37.5 symbols/second, resulting in a 6.6-ms time difference (20 ms compared to 26.6 ms) in symbol length. By intentionally making the phase shift information unusable during that 6.6-ms interval, the transmitted symbol of the test modem simulated that of the full-scale system.

The encoding technique of the prototype modem differed from that of the full-scale system (as shown in Figure 3) in that every symbol contained data and phase updating information. Therefore, at the receiver, provision was made for using only every other symbol for phase updating of the reference, consistent with the technique that would be employed in a full-scale system.

Scaled DEFT Modem

The DEFT modem tested was a quarter-scale version (i.e., 750 bits/second) of the proposed full-scale (3000-bit/second) system. The test modem contained 22 phase reference tones and the 2 synchronization tones as would be used in the full-scale system. Only 10 information channels (10 tone pairs) were required to achieve the 750-bit/second capability, and these channels were placed such that 5 channels were at the low end of the baseband and 5 were at the high end.

SECTION IV

DATA ANALYSIS AND RESULTS

INTRODUCTION

This section describes the results of the test data obtained during field testing of the modems previously described over the leased commercial circuit between Pretoria, South Africa, and Riverhead, Long Island. The test circuit was operated during two 30-day test periods, which included the month of April, 1964, and the period from 15 June to 14 July 1964. The accumulation of test data was hampered by all the usual difficulties of HF radio communications.

A major limitation was the length of time that a usable circuit was available each day. After some experience was gained with the circuit, it was found that, generally, data runs could be attempted for only about 16 hours of each 24-hour period. During the hours from 0100 to 0900 GMT, the circuit was not usable because of extreme QRM or lack of signal strength.

A particular difficulty was the amount of QRM experienced throughout the entire test period. Some QRM was experienced at nearly all times of the day, and was particularly severe on the nighttime frequencies. At times, it was possible to sidestep this type of interference by moving the RF carrier frequency by 500 to 1000 cycles in an attempt to move away from the interfering signal.

Frequent downtime of the leased Teletype Order Wire (OW), used to coordinate test activity at each end of the link, caused some hindrance to test operations during the April test period. Since the teletype OW was transmitted on the same RF carrier as the test transmission, it was subject to the same outages. Moreover, since the teletype communications were ARQ-protected, it was necessary for a complete radio path to exist in both directions for communications to be possible. During the June/July period, after the link was established via Tangiers, it was no longer a bothersome factor.

Finally, test data time was limited by circuit outages experienced during frequency changeovers. This problem was alleviated somewhat by frequency dualing whenever extra transmitters were available.

In spite of the above-mentioned operational difficulties, the maintenance of a 16 hour a day, 7-day a week test schedule was responsible for the accumulation of some 100 hours of test data during each of the 30-day test periods.

The data that was used in the analysis of comparative modem performance, described in this section, was that obtained during the 15 June to 14 July test period. Since a sufficient quantity of good quality test data was accumulated during this period, such comparative performance analyses were possible.

Despite the amount of test data collected during the first test, it was not used for purposes of comparative analyses of data modem performance since there were many equipment changes (particularly on the KATHRYN system), an unexplained 150-cps intermodulation problem which cropped up occasionally, and difficulties in equating results since equal energy per bit weighting was not used for the first test.

Generally, equal energy per bit is an a priori conclusion in a modem evaluation program since full-scale modems, all of which operate at identical bit rates and have identical transmitter power available, are compared. When all available energy from the transmitter is utilized by a data system in transmitting information, then energy per bit (E_o) is the transmitter power divided by the bit rate, i.e., $E_o = P(BR)$.

Since the objective of the tests was to evaluate scaled versions of 3000-bit per second modems and since the modems evaluated during the MITRE tests either differed in bit rates or wasted available energy (by transmitting unused tones, etc.), it became necessary to adjust the transmitter power for each modem so that the data derived from the tests could be presented in the manner shown in Figures 13 through 35.

Any comparative analysis of modems for which the equal energy per bit criterion is not followed must show energy per bit divided by noise power density (E_o/N_o --- which is propotional to S/N ratio) as a variable. Modem power level adjustments are described in the Appendix.

During the April test period, power level settings for the various modems were made according to the usual procedure of the transmitting station. This method was based on an optimum power versus linearity procedure and not on the energy per bit considerations.

With regard to the data presented herein, it should be noted that numerical estimates of comparative performances have not been made, and deductions are limited to qualitative observations of the various graphical presentations derived from the test data.

CLASSIFICATION OF DATA AND DATA REDUCTION

Types of Data Plotted

The data used to plot the various graphs and diagrams were classified according to the amount of refinement and selection done. The classifications are as follows:

Class I. All data except for

(a) runs which showed error rates greater than 1.0×10^{-1}, for which a "no circuit" condition or malfunction was assumed;

(b) runs which contained synchronizing errors of the type explained in Section III, and

(c) runs made on a redundant basis.

Class II. Class II data is a refinement of Class I data, achieved by deleting

(a) runs known to contain radio interference (QRM) within the operating of the modem being considered, unless the given modem was running in a QRM environment in parallel with a modem not in a QRM environment but still operating at a lower error rate, and

(b) runs which experienced moderate to severe static, where moderate to severe is defined to be greater than 100 static spikes per run.

Class III. Class III data consists of parallel runs only of Class II data quality. Certain parallel runs were deleted from Class III data, however, including:

(a) parallel run data for which differences in error rate of two orders of magnitude were experienced, suggesting a possible malfunction in the modem experiencing the higher error rate, and

(b) several runs of unusually long duration, which, if included, would be such a significant percentage of the run time being considered that they would tend to bias the results. That is, for the time distributions discussed on page 41, the data points would tend to reduce the effectiveness of the sideband swapping procedure used during collection of the test data in an attempt to average any difference which might have existed between parallel channels.

Data Reduction

Initially, all bit error rates were calculated and tabulated along with any pertinent remarks concerning synchronizing errors or redundant operation. Error rates are the average error rates for each run. AGC tapes were analyzed, and S/N ratio and an estimate of the number of static crashes per run were recorded. If static crashes occurred, they were categorized in a decade fashion; that is, category one refers to 1 to 10 crashes per run, category two to 10 to 100 crashes per run, etc.

QRM information was obtained from a playback through an audio spectrum analyzer of magnetic tape recordings made of every run and one minute of the "dead time" between runs. The runs observed were those noted as QRM runs in the receiving station log, parallel runs with differences in error rates of a half-order of magnitude, and runs which had unusually high noise as observed on the AGC tapes during the "dead time" preceding or following the run. When QRM was observed in the passband of the receiver, it was placed in one of six categories. The first three categories constitute the co-channel interference cases; that is, when QRM was observed in the operating baseband of the modem considered, it was classified in one of the first three categories. The three categories are severe, moderate, or weak, depending on the strength of the interference relative to the noise level. The last three categories refer to adjacent channel interference and are classified by the same criteria as the co-channel case.

RESULTS

Types and Descriptions of Graphical Presentations

Scatter Diagrams

Scatter diagrams were drawn for all parallel runs of the Class II variety. While these diagrams are somewhat more difficult to interpret than other presentations in this report, they do have the advantage of displaying the most information concerning the comparative performance of the respective modems. The one parameter not shown on these diagrams is the time weighting of each point; that is, the percentage of total test time that a particular run represents. It may be argued, however, that each run should contribute the same amount of information. This is especially true for comparisons of parallel runs where the various points represent data taken on the same channel during the same time interval. The "same channel" assumption should be quite good since sideband switching was performed systematically in order to average equipment differences, and since the vast majority of data containing "nonwhite" interference was removed. Other diagrams in this report present error rates as time distributions, but have the disadvantage of showing average results rather than simultaneous comparisons.

The diagonal in a scatter diagram is the curve of equal performance, and divides the diagram into two fields: (1) the area where $BER_B < BER_A$, and (2) the area where $BER_A < BER_B$. The degree of advantageous inequality is roughly determined by the amount of excursion from the equal performance curve. The roughness results from the fact that the points are plotted in a logarithmic fashion. A general statement is sought which concludes that the better modem is the system which has the greatest number of points in "its half" of the diagram. The range of error rates over which this general deduction is valid and the degree of confidence with which it is made is subject to a fine grain analysis, however.

For the general statement (that A is better than B) to be true, certain combinations of criteria must be met. The sample size, for instance, must be sufficiently large and the distribution sufficiently one-sided to enable a confident estimate of comparative performance to be made. If all the points are fairly close to the equal performance line, then, in order to draw a confident conclusion, the sample size must be much larger than if the points tended to show a one-sided distribution at a significant distance from the equal performance line.

In addition to the confidence required, the general conclusion may not be allowable if the distribution of points tended to show a one-sided distribution at a significant distance from the equal performance line.
In addition to the confidence required, the general conclusion may not be allowable if the distribution of points cross the equal performance line. For example, if A is favored at low error rates and B at high error rates, then the statement that A is a better modem under

bad conditions is an allowable argument and contradicts the general conclusion concerning modem A and modem B.

Although numerical estimates of confidence, etc., were not made, those cases of most interest tend to follow the basic arguments sufficiently well so that the conclusions drawn from these diagrams can be made with a high estimate of confidence.

Diagrams of Time Distribution of Error Rates

Two types of diagrams are presented which show error rates plotted as some function of time (actually percentage of test time). These diagrams are called Cumulative Performance Diagrams and Incremental Performance Diagrams, and represent average test results.

Cumulative Performance Curves. The first type of time distribution presentation is a standard type of graph, where the percentage of test time that a modem equalled or exceeded a given error rate is plotted. The points derived, although spaced a decade apart, are invariant; that is, no matter how fine the grain analysis performed, the additional points obtained may define the curve better but do not, in any way, alter the original points.

The "goodness" criterion for this type of curve is quite evident as long as the curves do not cross over. A crossover may result from the type of time distribution of error rates mentioned in the next subsection as well as from the inclusion of data points from unequal run times as discussed on page 42.

Incremental Performance Diagrams. The second type of graph is a histogram that shows the percentage of test time during which a given modem ran within a given class limit. Class limit is defined by the inequality: $1.0 \times 10^{-n} \geq \text{BER} > 1.0 \times 10^{-(n+1)}$. Other ways of stating this are that the diagram shows how frequently a given modem ran within a given class limit or that the histogram defines the boundary of a minimal region into which all experimental points lie, with the stipulation that each segment of the region contain at least one point.

Since the area under any histogram is equal to the area under any other histogram, one might consider, as a measure of goodness, the magnitude of the first central moment about the ordinate axis. This implies that the central moment is the average error rate which, of course, is a very crude estimate since the distribution of points within a given class limit has not been considered. The best application of this type of diagram is as an aid in analyzing the comparative performance at the various error rates. Ideally, the best modem would be one distributed primarily in the comparatively lower error rate classes. It may be, however, that while modem A ran a greater percentage of time at lower error rates than B, it also ran a greater percentage of time at higher error rates than B. This would be indicated by a fairly flat distribution for A and a peaked distribution for B. An example of this is the N. R. vs. KATHRYN presentation (Figures 28 (a) and (b)), which invalidates a general conclusion that A is better than B.

Limitations of the Time Distribution Diagrams. The two presentations are directly related in that one can be derived from the other; however, certain qualifications must be made concerning the interpretations. Since these diagrams represent average results, their validity is directly related to the amount of averaging done. For some cases, this amount is small.

Some additional degradation in the quality of these curves results from the fact that all runs were not of equal length. For instance, when parallel runs of KINEPLEX and KATHRYN are considered, each modem had two runs where the error rate was between 1×10^{-1} and 1×10^{-2}. The two KATHRYN runs totalled 13 minutes. This caused the Cumulative Performance Curves to crossover, (see Figures 21 (a) and (b)) whereas, had the runs been of equal length, this would not have occurred. The amount of degradation of this type decreases as the total data time being considered increases. In the example, the total test time was 183 minutes, which resulted in a 2.2 percent bias. Had the total test time been 1000 minutes, however, the bias would have been 0.4 percent.

Analysis and Discussion of Results

Although many graphical presentations are self-explanatory , it is believed that a brief discussion of the various figures is appropriate. The graphical presentations are not analyzed in the same order in which they were discussed above. Aggregate and parallel results are discussed separately and deductions made independently for each case. Conclusions based on the deductions of this section will be presented in Section V.

Aggregate Results from the Test

Cumulative Performance Curves. Figures 13 (a) and (b)* show Cumulative Performance Curves derived from test data of Classes I and II. These curves have the advantage of being derived from a large sample size (many runs), but do have several disadvantages in that the normalizing factors (total data time) differ for each modem and the runs are not concurrent. The bias introduced, however, is quite small. For example, DEFT and KINEPLEX ran error-free for 25 minutes and 27 minutes, respectively, during tht test. The individual error-free periods which contributed to these sums occurred during closely adjacent periods in time. If all runs had been concurrent and normalizing factors the same, the curves would most probably have converged at $X = 1 \times 10^{-6}$. This same convergence would have altered the curves by no more than 1 percent.

Incremental Performance Histograms. Figures 14 through 17 are Incremental Performance Histograms derived from Class II data, and are subject to the same conditions mentioned for Figures 13 (a) and (b).

Deductions. Using Figure 13 (b) and Figures 14 through 17, the following deductions, based on aggregate Class II data, can be made:

1. DEFT operated at better error rates than any other modem a greater percentage of the time except at error rates less than 1×10^{-5}, where its performance was about equal to that of KINEPLEX.

2. Except for the range of error rates 1×10^{-5} and less, KINEPLEX tended to operate at a slightly higher error rate than DEFT.

3. N. R./Rixon appears to have operated slightly better than KINEPLEX, but not as reliably as DEFT at the higher error rates and slightly worse than DEFT and KINEPLEX at error rates below 1×10^{-3}.

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*In the case of Figure 13, the (a) designates that the curve was plotted from Class I data, and the (b) designates the curve was plotted from Class II data.

4. KATHRYN tended to operate at relatively high error rates, compared to other systems, by a noticeable margin. Figures 13 (a) and 28 (b) show this explicitly, while a comparison of Figure 15 with Figures 14, 16, and 17 shows that the tendency was consistent; however, there appeared to be a lower bound on the error rate in the vicinity of 1×10^{-4} which was not noticed for the other systems.

Parallel Run Results from the Second Test

Cumulative Performance Curves. Figures 18 (a) and (b)* through 23 are Cumulative Performance Curves derived primarily from Class II data. Since runs were concurrent and normalizing factors consequently the same for all comparisons, the disadvantages of the aggregate presentations are not incurred. A problem of sample size begins to become apparent, however. For KATHRYN vs. DEFT and KINEPLEX vs. DEFT, the sample size is fairly large, and a typical individual run of 10 minutes represents only 2 to 3 percent of the total run time. This implies that a good averaging is possible and that one or two "oddball" runs will not shift the curve significantly. For the remaining curves, the percentages of total test times represented by individual runs are larger. For KATHRYN vs. KINEPLEX, the amount is between 5 and 6 percent; for N. R./Rixon vs. DEFT, it is between 6 and 7 percent; and for N. R./Rixon vs. KINEPLEX, approximately 10 percent. Since the sample size is fairly small, the argument presented on page 41, concerning unequal run times, also becomes pertinent. It is obvious, therefore, that some care must be taken in ascertaining the confidence with which any deductions are made.

Incremental Performance Histograms. The Incremental Performance Histograms, Figures 24 (a) and (b) through 28 (a) and (b), are subject to the same limitations mentioned above for the Cumulative Performance Curves. It is interesting to note that there is a correlation between the total data times and the regularity of the distributions; that is, for the smaller sample sizes, the distributions tend to have more than one peak.

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*Beginning with Figure 18, the (a) designates that the curve was plotted from Class II data, while the (b) designates that the curve was plotted from Class III data.

Scatter Diagrams. Figures 30 through 35 are Scatter Diagrams of test data for parallel runs. Class II data appears on these diagrams as points. Circled points indicate that Class II data was deleted to form Class III data. It should be pointed out that for error-free runs, a bit error rate of 1.0×10^{-6} was assumed. As was previously mentioned, the Scatter Diagram conveys more information than any other single presentation. This is especially true where sample size is involved, since no other graph considers sample size. An example of this is the comparison between DEFT and N. R./Rixon. The Cumulative Performance Curve shows a crossover which favors N. R./Rixon at error rates less than 10^{-5}. The Scatter Diagram (Figure 33), however, shows that this phenomenon is the result of only one run.

Deductions. The following deductions are based only on the graphical analysis of parallel comparisons:

1. For the parallel comparison of DEFT and KINEPLEX, the Performance Curves indicate that the two systems operated quite close to one another, with DEFT showing a slight edge at the lower error rates and KINEPLEX a very slight edge at the higher error rates. The Scatter Diagram, however, shows that when KINEPLEX was running at bit error rates between 1×10^{-1} and 1×10^{-3}, 15 runs were quite close to the Equal Performance Line, with 7 favoring DEFT and 8 favoring KINEPLEX. In this same range, there are 6 major excursions favoring DEFT and 1 favoring KINEPLEX. When KINEPLEX was running at error rates below 1×10^{-3}, there were 10 runs which might be considered close to the Equal Performance Line, with an even scattering of 5 on each side. Counting the more significant excursions, there are 9 favoring DEFT and 4 favoring KINEPLEX. On the basis of the above discussions (particularly the Scatter Diagram discussion), it appears that DEFT did at least as well as, and tended to be somewhat better than, KINEPLEX. It also appears this statement can be made without qualification.

2. For the parallel comparison of DEFT and KATHRYN, all presentations indicate that DEFT outperformed KATHRYN by a significant margin.

3. For the parallel comparison of DEFT and N. R./Rixon, the Performance Curves are somewhat irregular because of the small sample size used in averaging. The Scatter Diagram shows that DEFT tended to be favored most of the time, with a fairly wide distribution of excursions for the 24 points of wide excursion, however. Nevertheless, the one-sided distribution of points in favor of DEFT tends to indicate a superiority over N. R./Rixon. Some qualification must be made, however, since very few points appear at either the low error-rate or high error-rate

comparisons. Thus, from the Scatter Diagram, we can deduce, with some confidence, that when N. R./Rixon ran at a bit error rate less than 1×10^{-2} but greater than 1×10^{-4}, DEFT was shown to be superior. Outside of this margin, a confident estimate cannot be made because of the small sample size.

4. For the parallel comparison of KINEPLEX and KATHRYN, a crossover on the Cumulative Performance Curve shows KINEPLEX to be favored at error rates somewhere below 1×10^{-2}. The crossover results from the fact that KINEPLEX ran a greater percentage of the test time within the class limit $1 \times 10^{-1} \geq \text{BER} > 1 \times 10^{-2}$, as shown on the Incremental Performance Histogram.

A closer look at the data, however, showed that the effect resulted from the unequal run time argument mentioned on page 42. Both modems ran in the previously mentioned class limit twice; however, the two runs during which KATHRYN ran in the particular class limit totalled 9 minutes and the corresponding test time for KINEPLEX was 13 minutes.

The Scatter Diagram shown in Figure 32 gives a much better picture of the comparative performance. Figure 32 shows that when KATHRYN was operating within the limit $1 \times 10^{-1} \geq \text{BER} > 1 \times 10^{-2}$, only one significant excursion favoring KINEPLEX is evident, and no significant deduction can be made from this. When KATHRYN was operating at error rates between 1×10^{-2} and 1×10^{-3}, a trend in favor of KINEPLEX begins to show. However, if only Class III data is considered, the advantage is still not significant; that is, when KATHRYN was operating within the stated limits, five minor excursions favor KINEPLEX, five major excursions favor KINEPLEX, and four major excursions favor KATHRYN. The KINEPLEX advantage becomes more evident at lower error rates, and the following deduction is made: KINEPLEX tended to outperform KATHRYN; however, the tendency was significant only at lower rates and, indeed, appeared insignificant at the higher error rates.

5. For the parallel comparison between KATHRYN and N.R./Rixon, the Performance Curves are derived from a small sample size and tend to be irregular. The Scatter Diagram shows that the sample space is made up of only 11 points, and these tend to favor KATHRYN at the higher error rates and N.R./Rixon at the lower error rates. Although a deduction might be drawn from the Scatter Diagram, it is believed that the extremely small sample size precludes this.

6. For the parallel comparison between N. R./Rixon and KINEPLEX, the sample size is composed of 19 widely scattered points. There appears to be a distribution in favor of KINEPLEX at error rates above 1×10^{-3};

however, this advantage is not decisive. For error rates below 1×10^{-3}, the sample size is so small and the scattering so uniform that no decision can be made concerning the advantage of one system over the other.

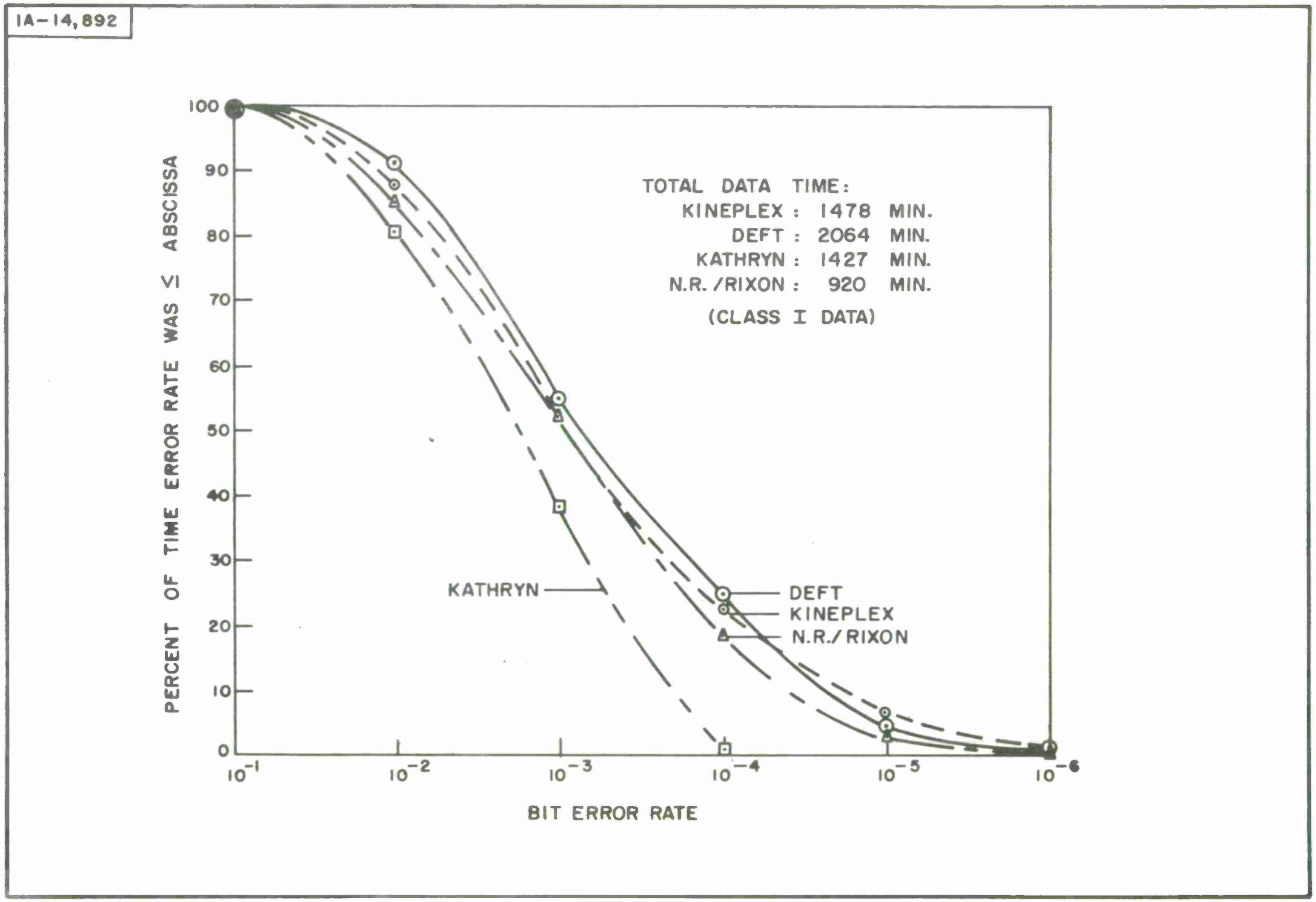

Figure 13(a) Cumulative Performance Curves for KINEPLEX, DEFT, KATHRYN and N.R./Rixon - Class I Data

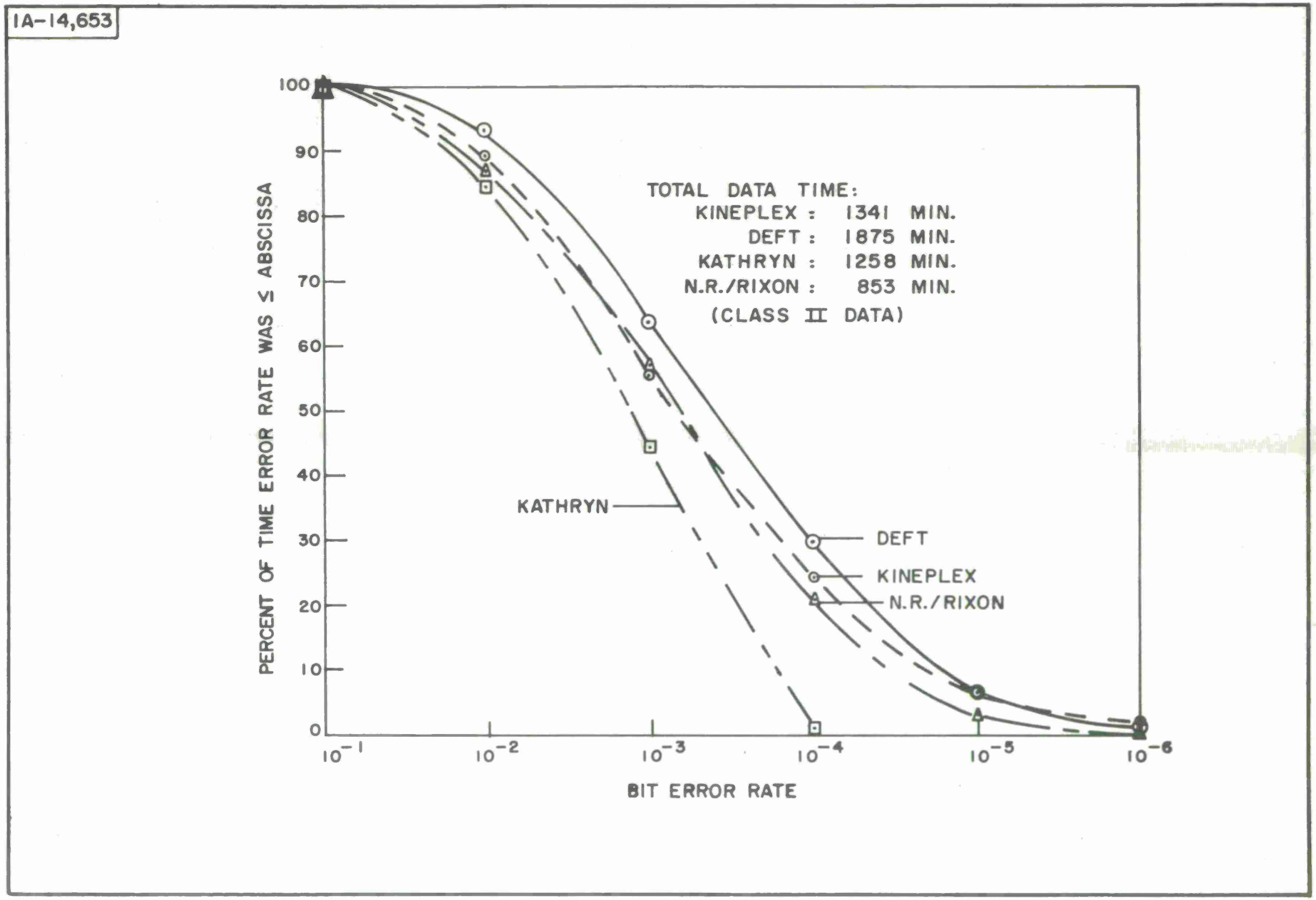

Figure 13(b) Cumulative Performance Curves for KINEPLEX, DEFT, KATHRYN and N.R./Rixon - Class II Data

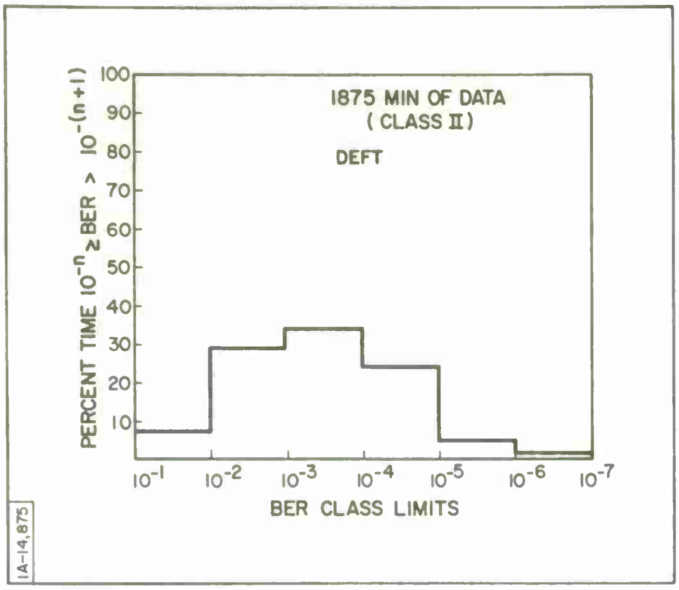

Figure 14 DEFT

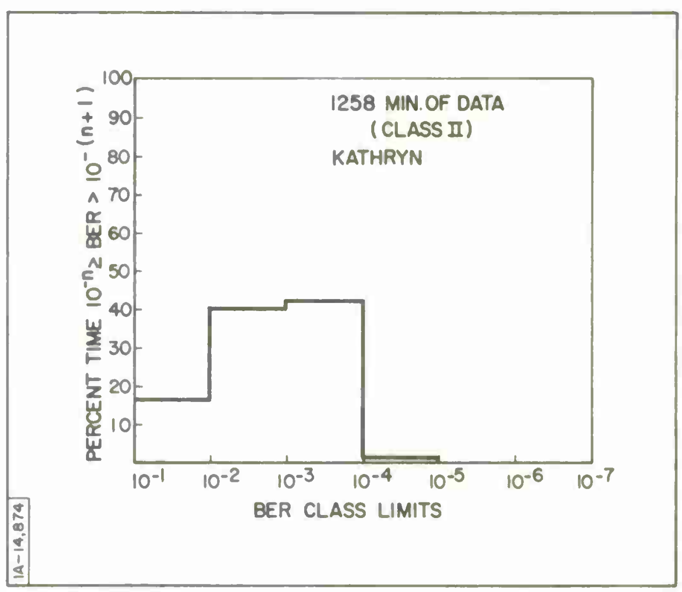

Figure 15 KATHRYN

Incremental Performance Histograms - Class II Data

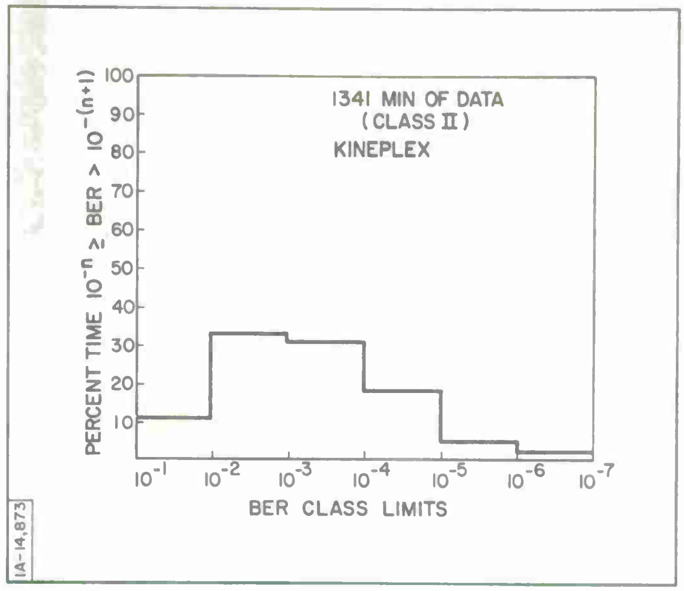

Figure 16 KINEPLEX

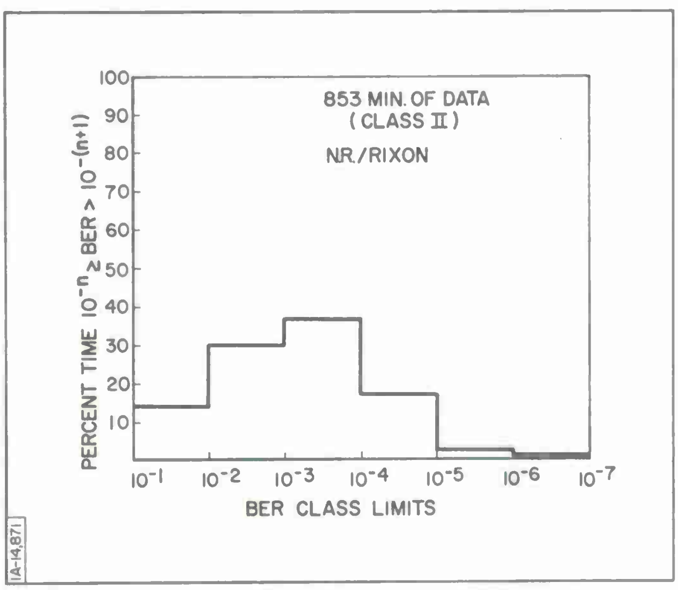

Figure 17 N.R./Rixon

Incremental Performance Histogram - Second Test, Class II Data

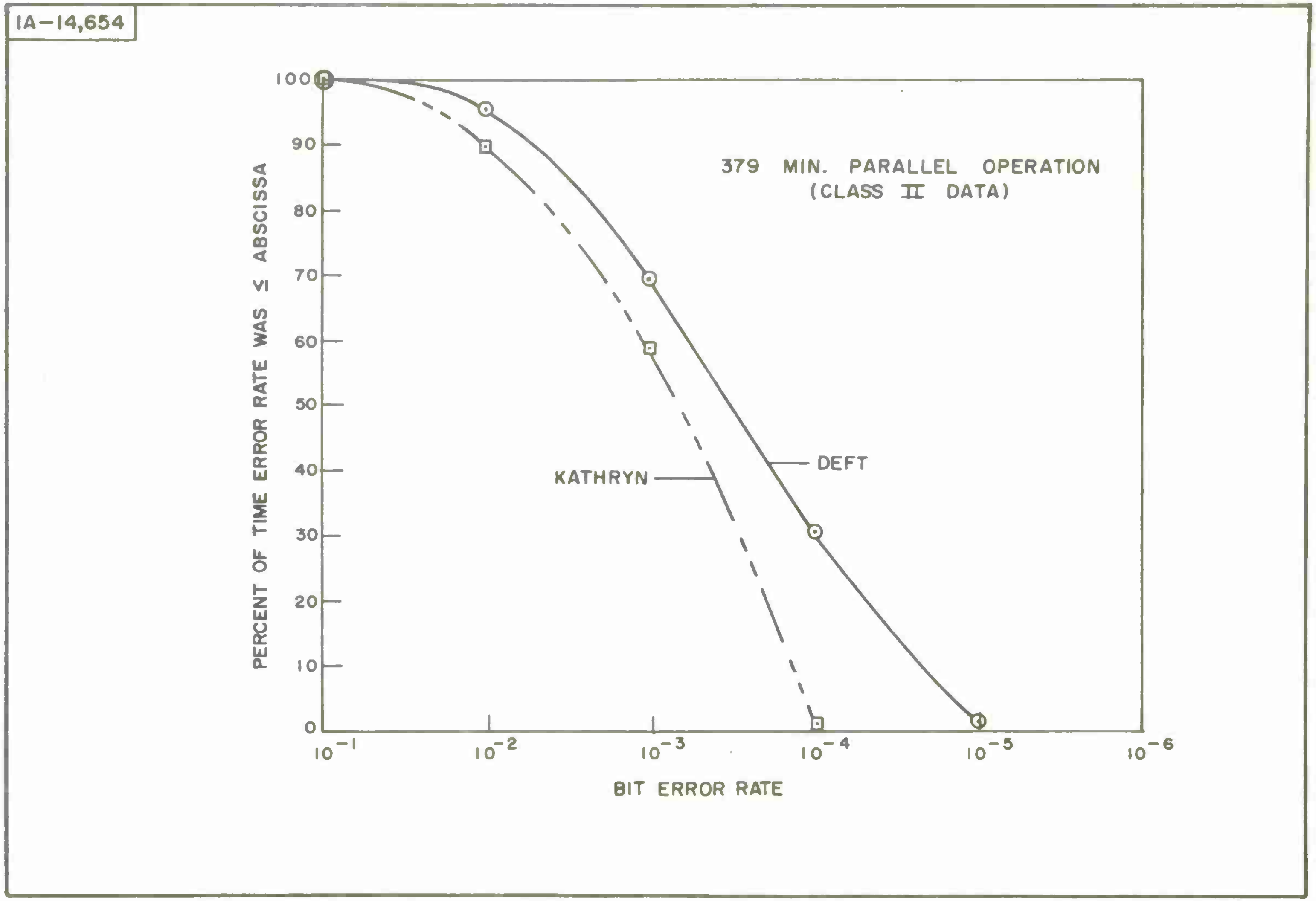

Figure 18(a) Cumulative Performance Curves, KATHRYN vs. DEFT - Class II Data

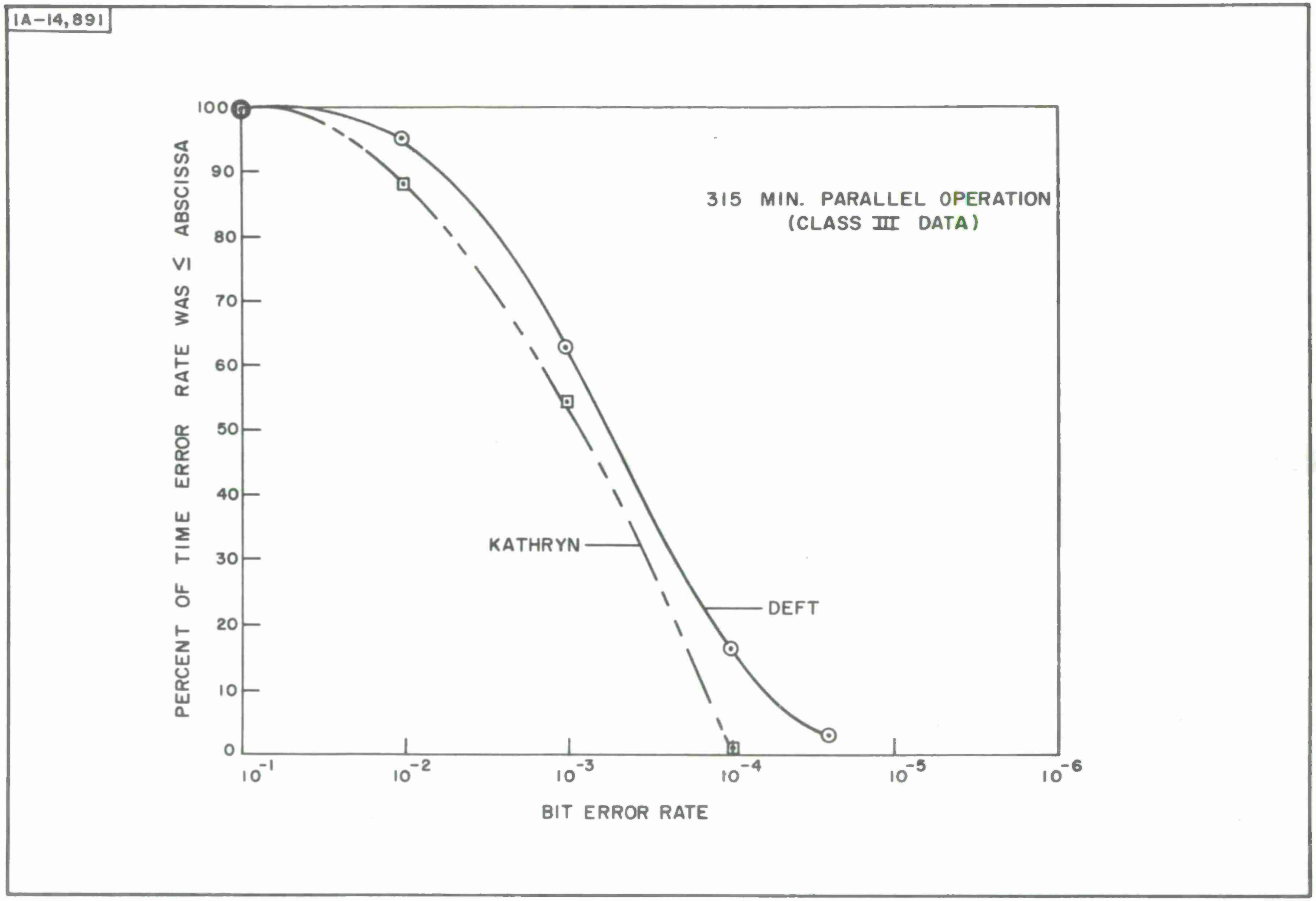

Figure 18(b) Cumulative Performance Curves, KATHRYN vs. DEFT - Class III Data

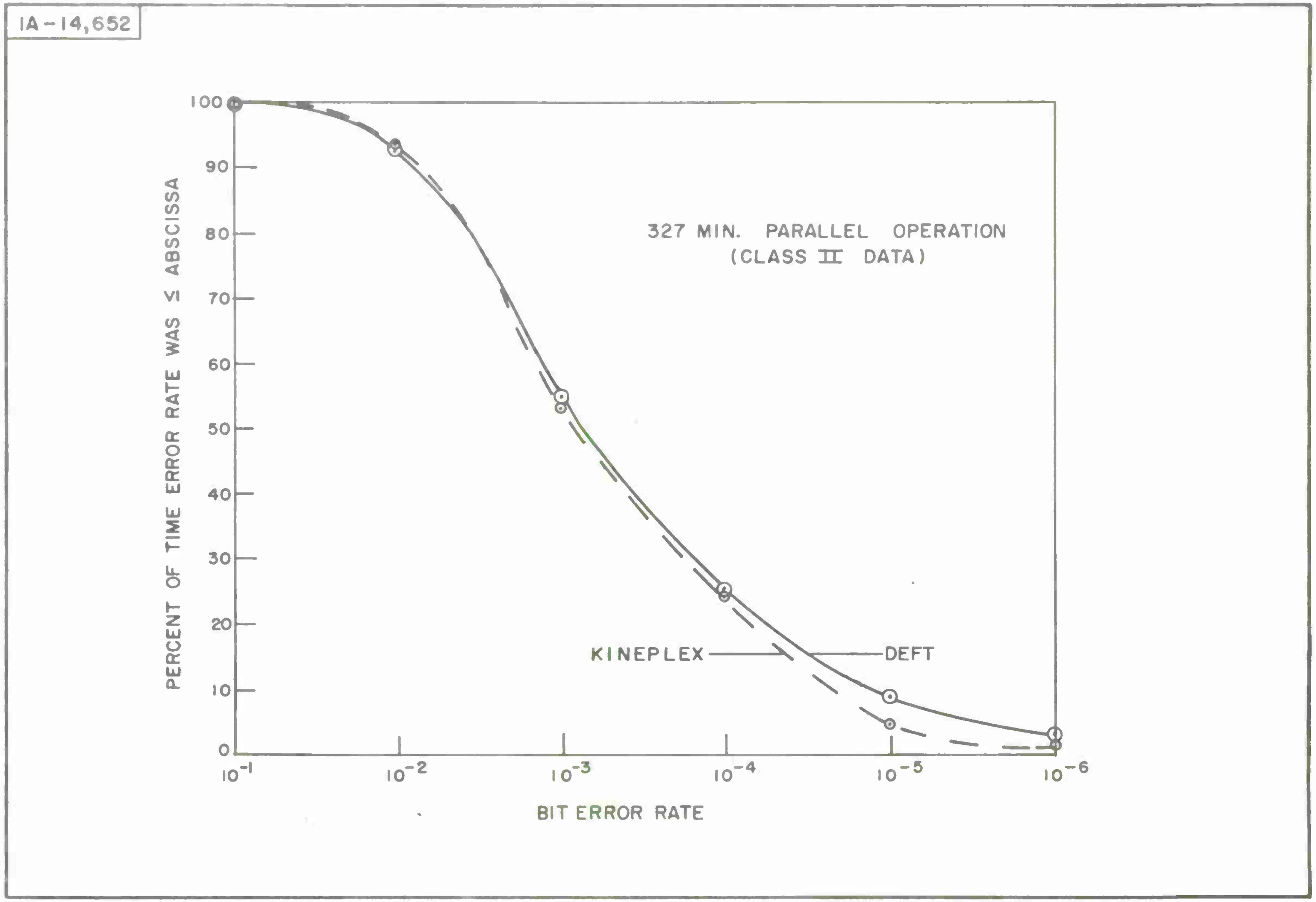

Figure 19 Cumulative Performance Curves, KINEPLEX vs. DEFT - Class II Data

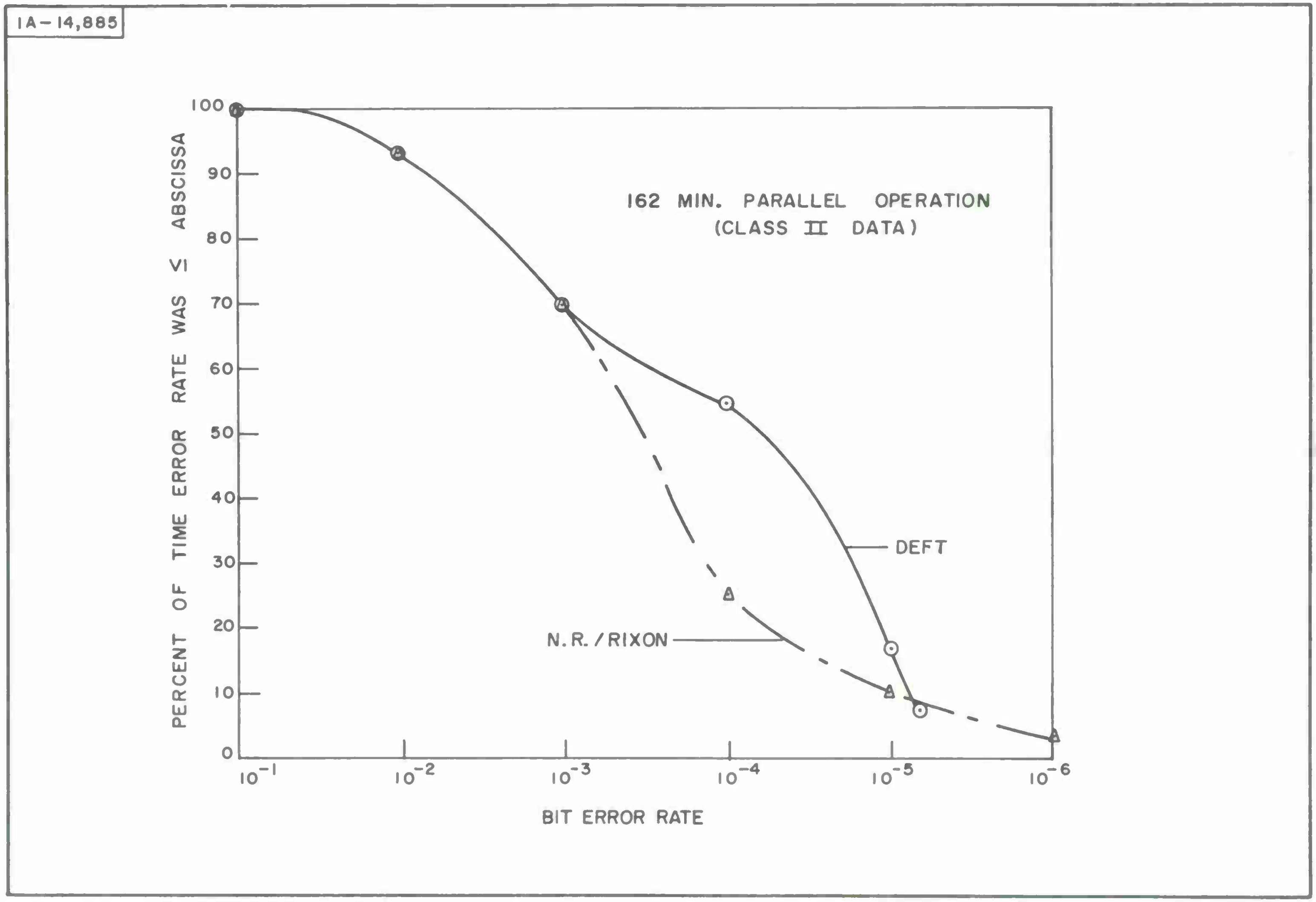

Figure 20 Cumulative Performance Curves, N.R./Rixon vs. DEFT - Class II Data

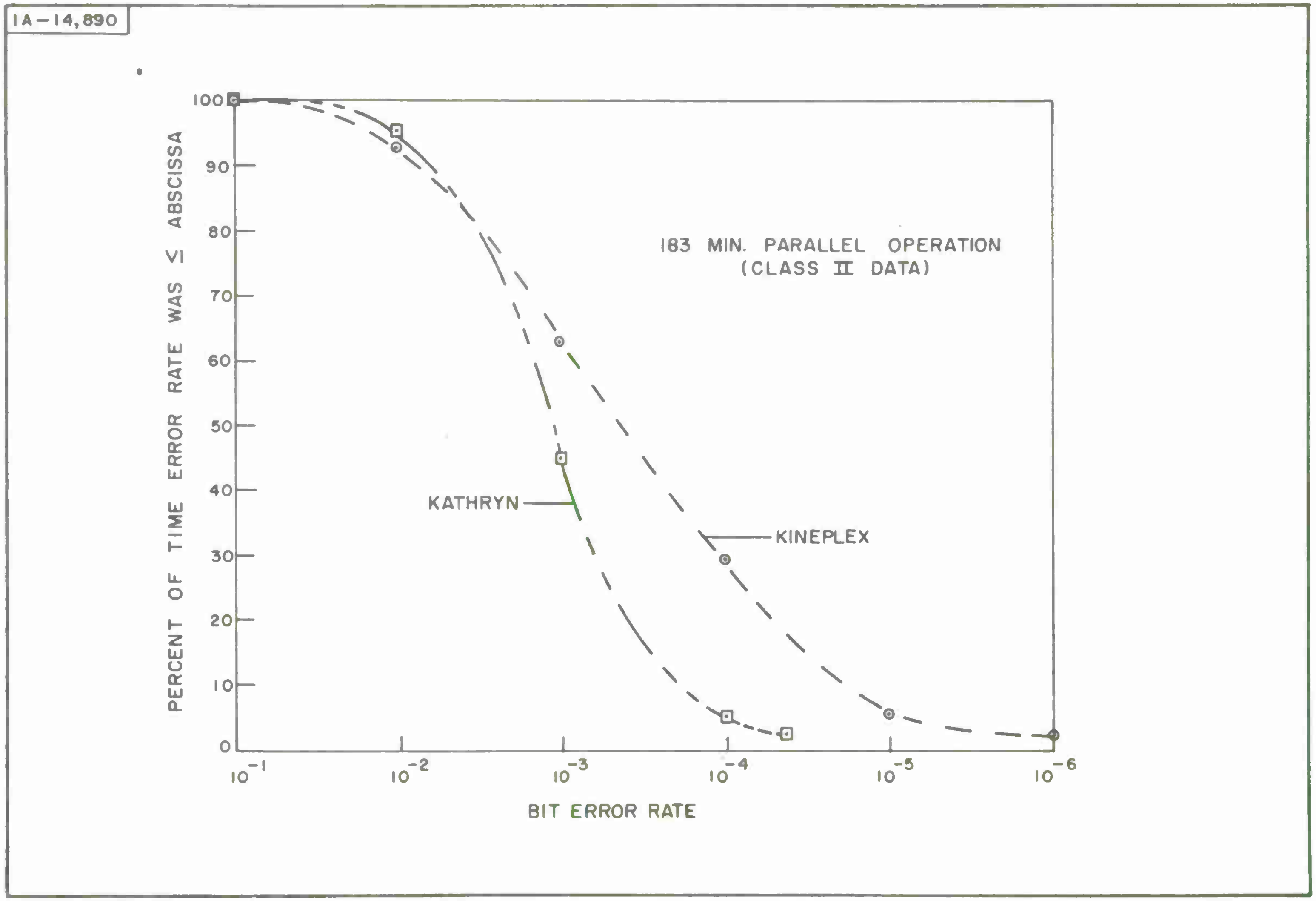

Figure 21(a) Cumulative Performance Curves, KATHRYN vs. KINEPLEX - Class II Data

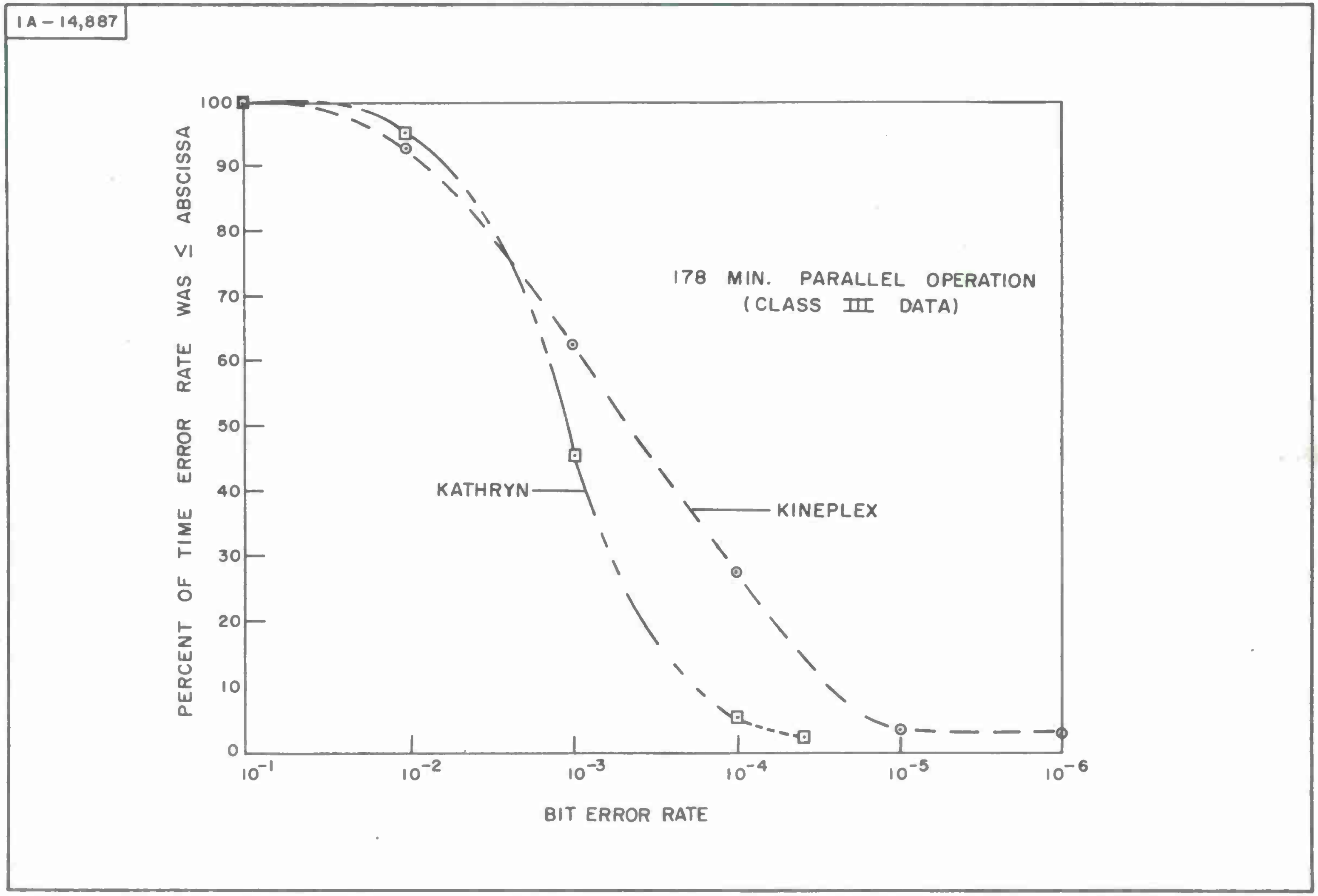

Figure 21(b) Cumulative Performance Curves, KATHRYN vs. KINEPLEX - Class III Data

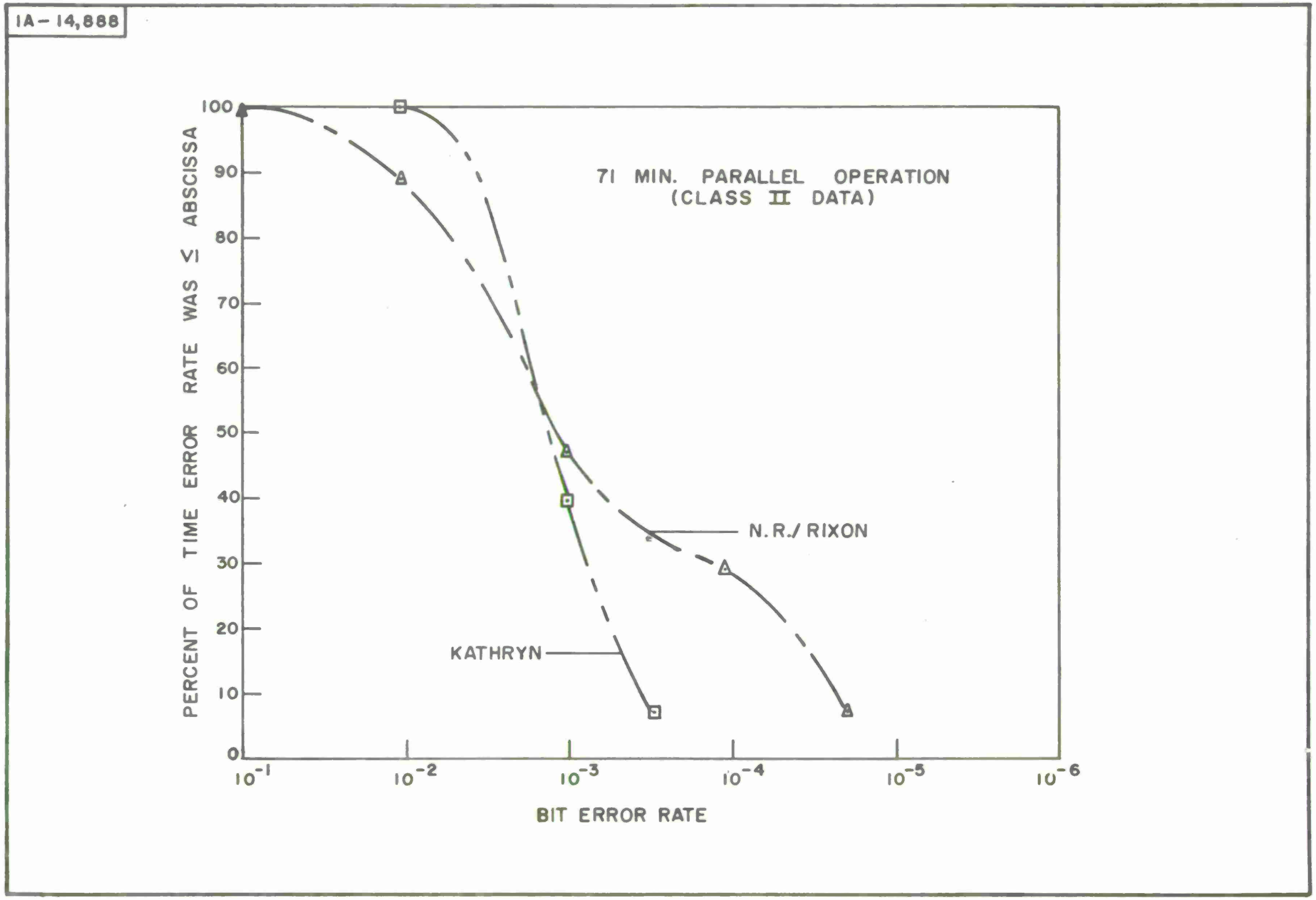

Figure 22(a) Cumulative Performance Curves, N.R./Rixon vs. KATHRYN - Class II Data

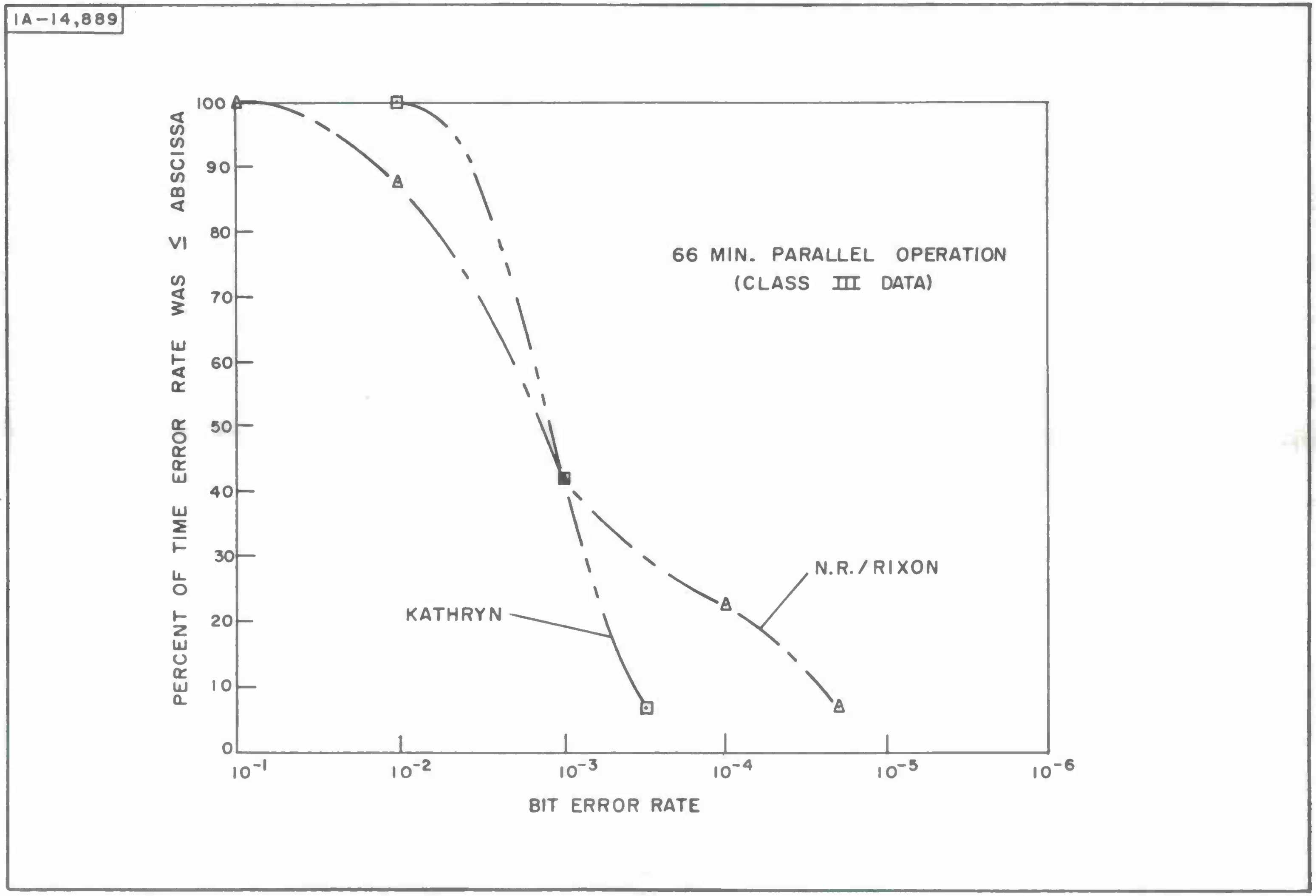

Figure 22(b) Cumulative Performance Curves, N.R./Rixon vs. KATHRYN - Class III Data

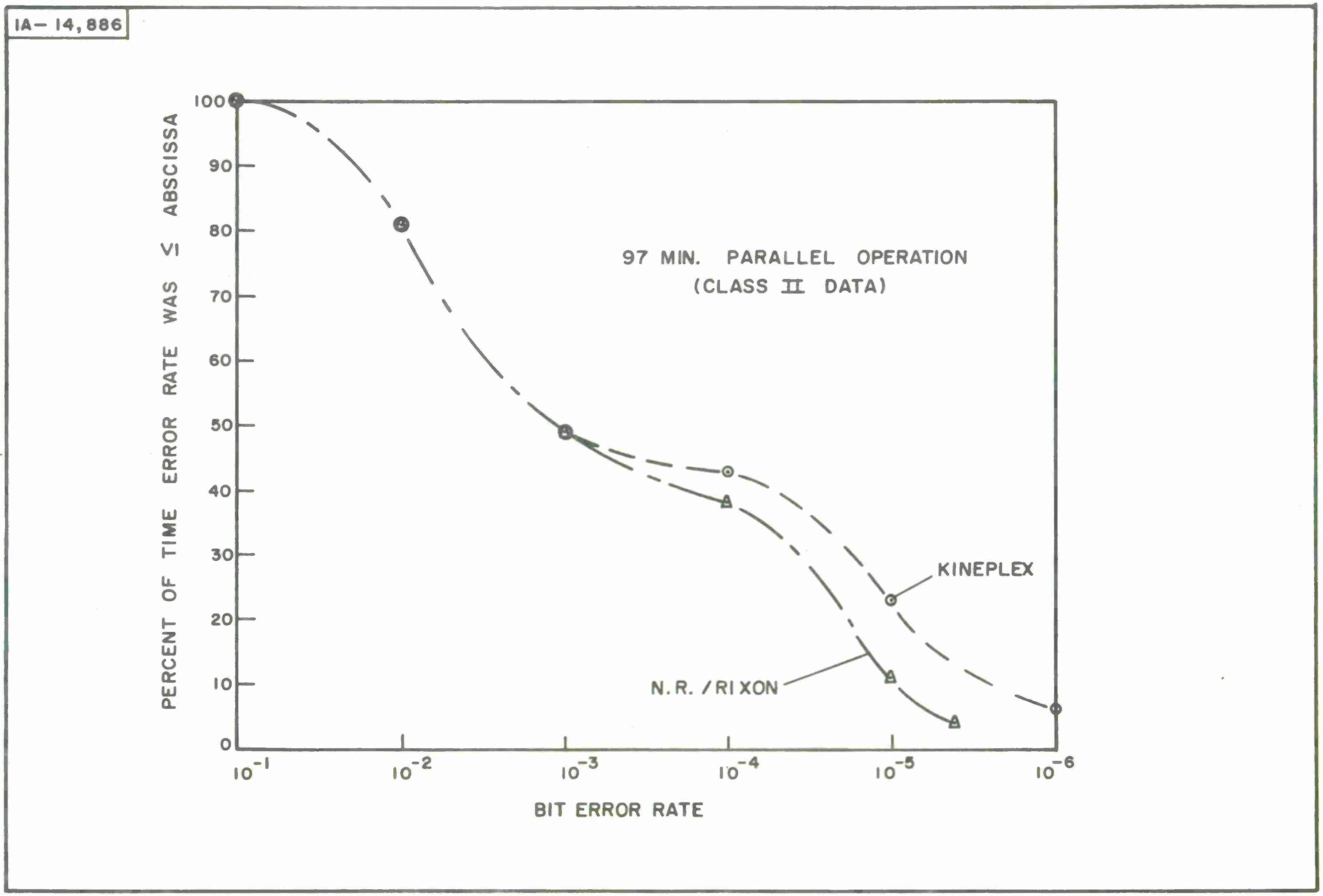

Figure 23 - Cumulative Performance Curves, N.R./Rixon vs. KINEPLEX - Class II Data

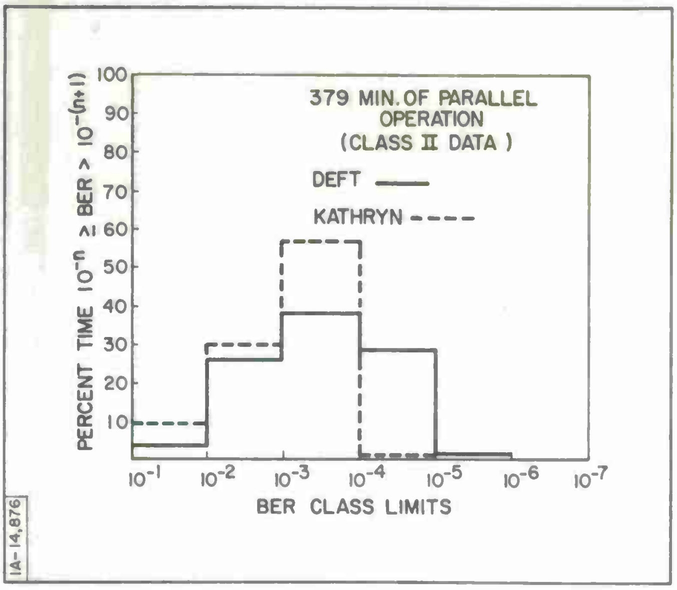

Figure 24(a) DEFT vs. KATHRYN - CLASS II DATA

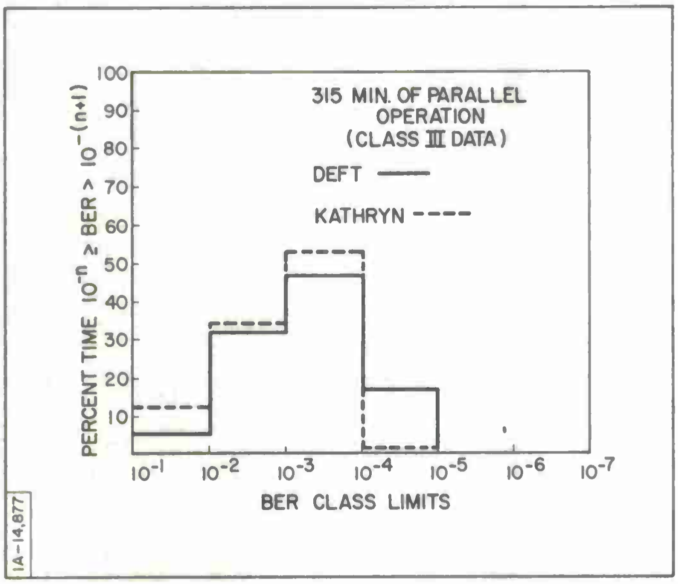

Figure 24(b) DEFT vs. KATHRYN - Class III Data

Incremental Performance Histograms

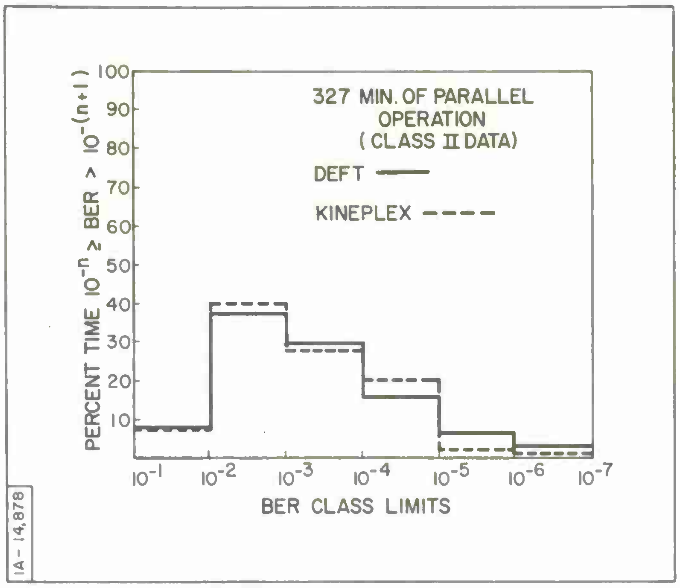

Figure 25 DEFT vs. KINEPLEX

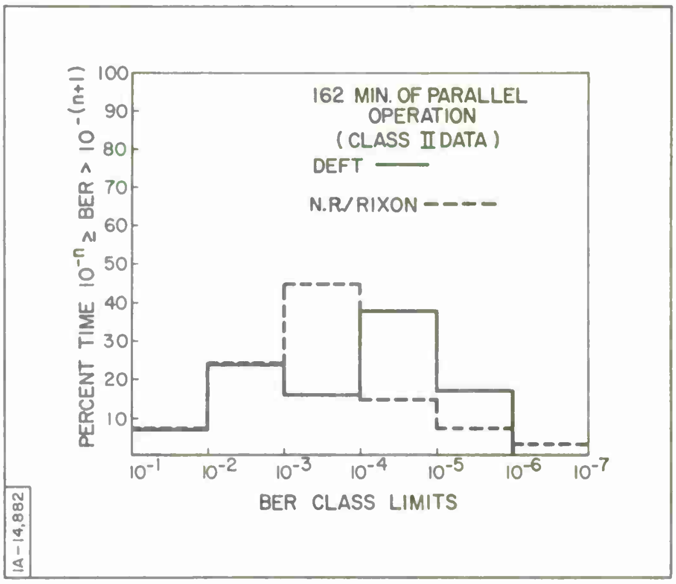

Figure 26 DEFT vs. N.R./Rixon

Incremental Performance Histograms - Class II Data

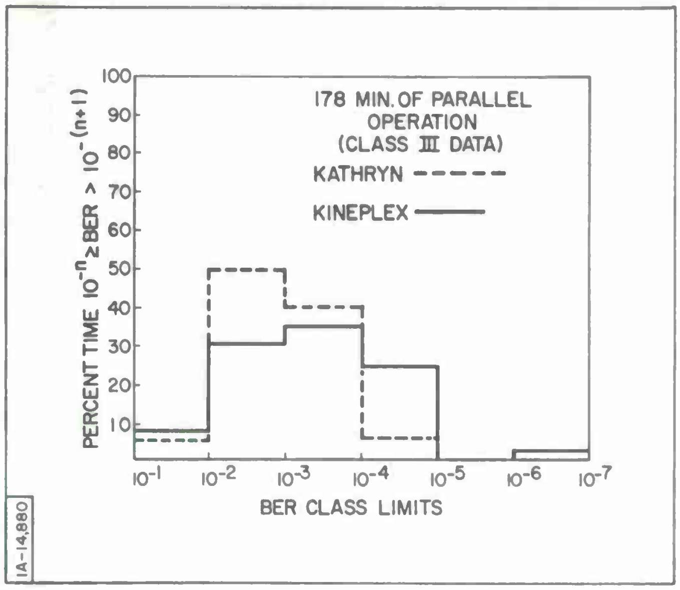

Figure 27(a) KATHRYN vs. KINEPLEX - Class II Data

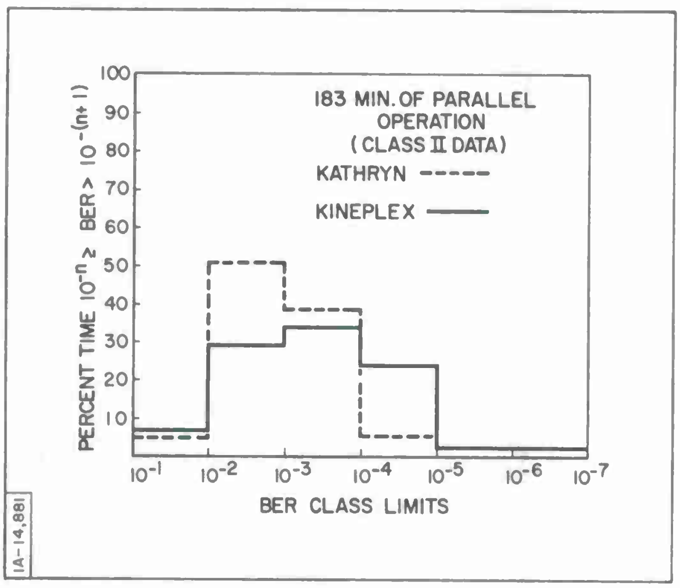

Figure 27(b) KATHRYN vs. KINEPLEX - Class III Data

Incremental Performance Histograms

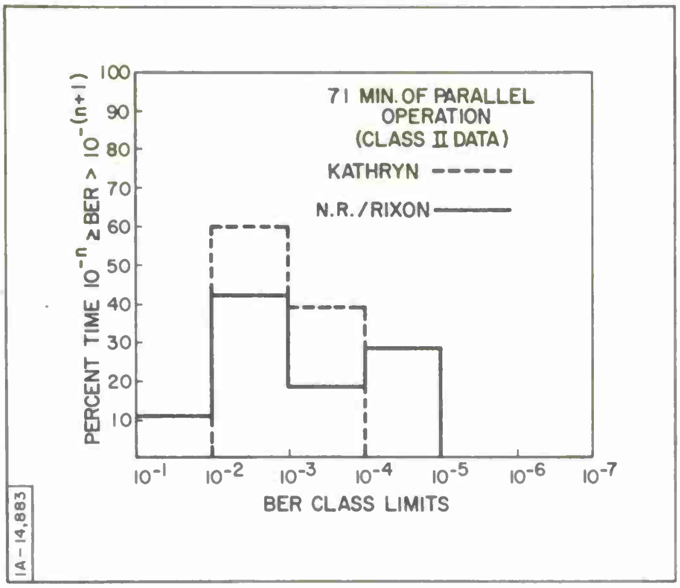

Figure 28(a) KATHRYN vs. N.R./Rixon - Class II Data

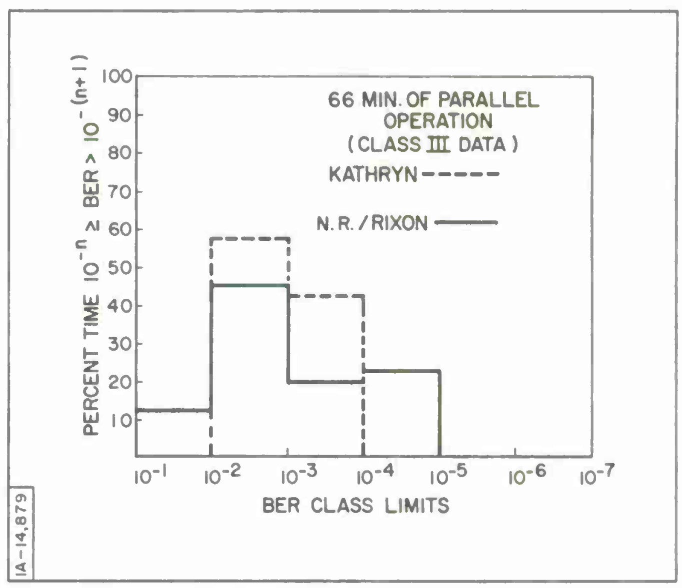

Figure 28(b) KATHRYN vs. N.R./Rixon - Class III Data

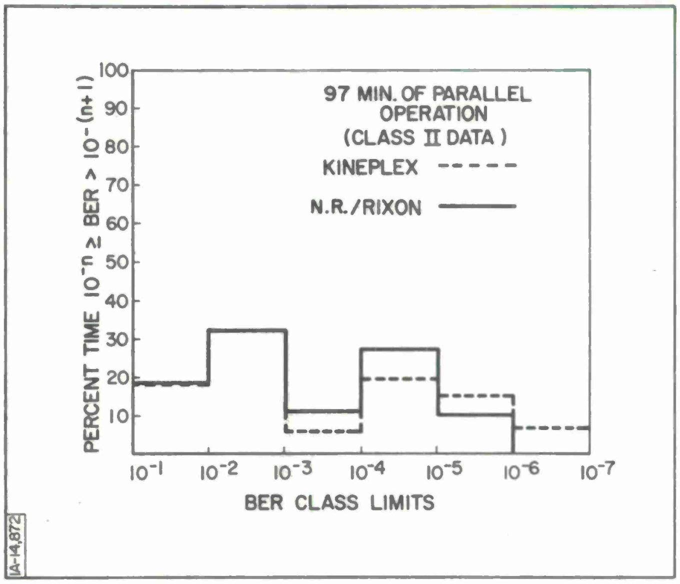

Figure 29 KINEPLEX vs. N.R./Rixon, Incremental Performance Histogram - Class II Data

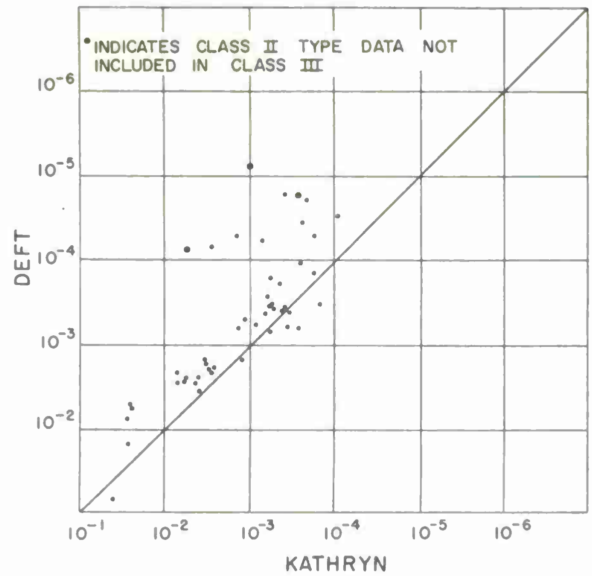

Figure 30 DEFT and KATHRYN

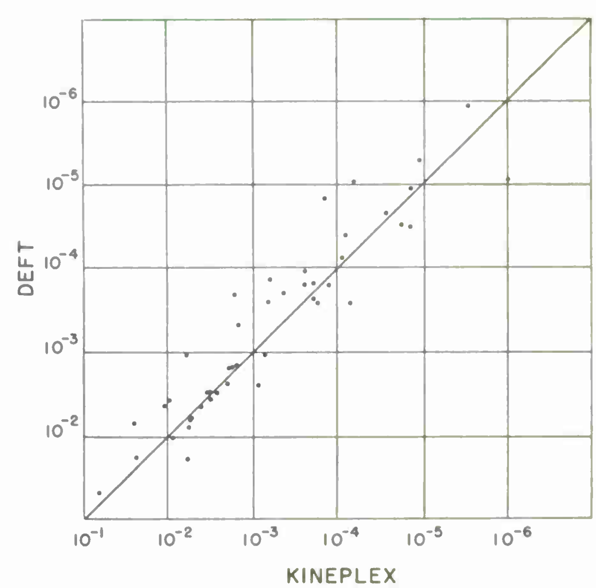

Figure 31 DEFT and KINEPLEX

Scatter Diagrams of Error Rates for Parallel Runs

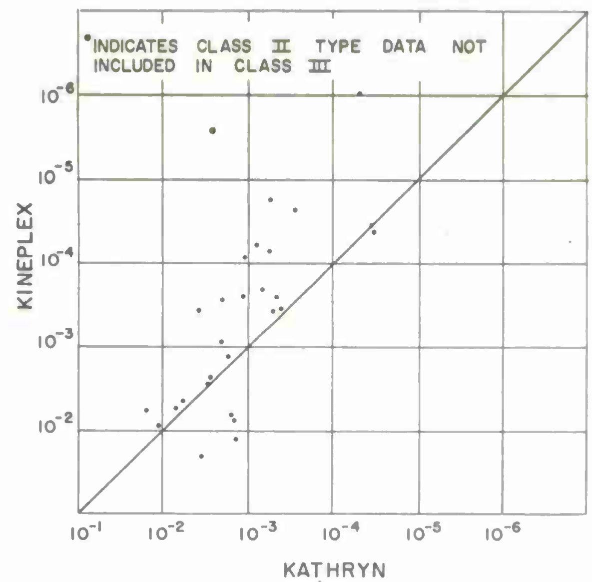

Figure 32 KINEPLEX and KATHRYN

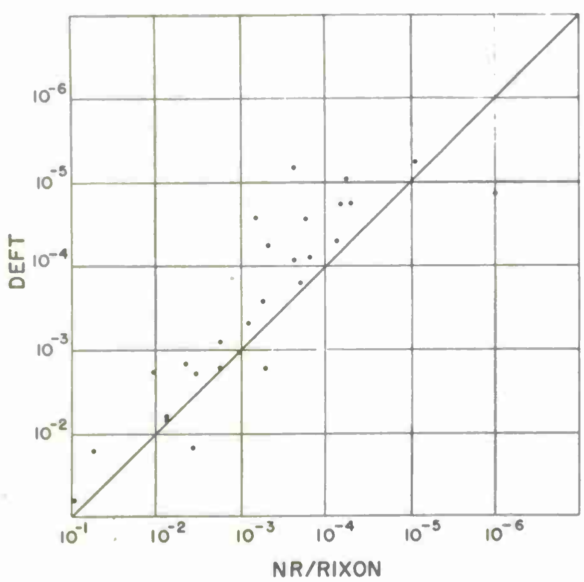

Figure 33 DEFT and N.R./Rixon

Scatter Diagrams of Error Rates for Parallel Runs

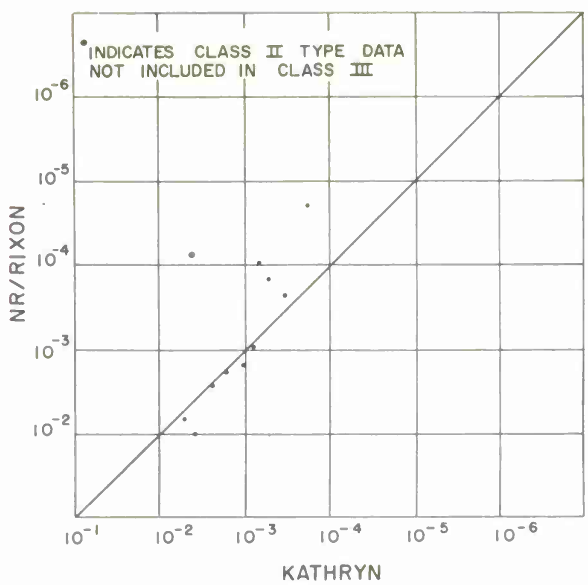

Figure 34 N.R./Rixon and KATHRYN

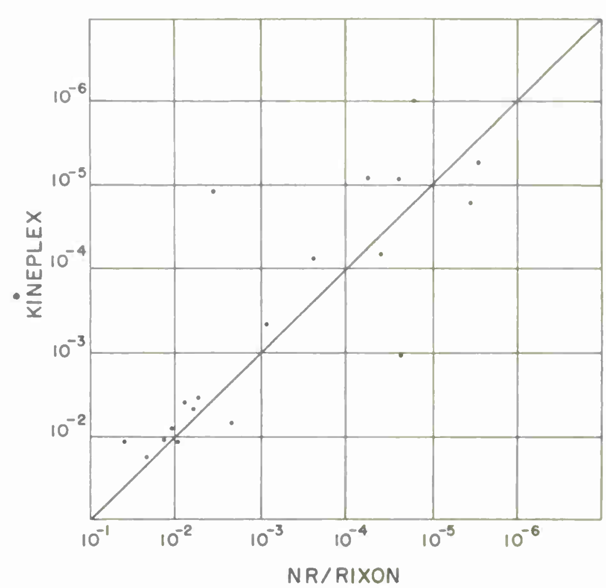

Figure 35 N.R./Rixon and KINEPLEX

Scatter Diagrams of Error Rates for Parallel Runs

SECTION V

CONCLUSIONS

DISCUSSION

The test results have been presented in Section IV, along with some discussion on the limitations of field testing over HF radio circuits. It is apparent from the discussion that an evaluation of the data modems on the basis of absolute long-term average error rate is, in itself, not too meaningful since the quality of the link itself plays a large role in the final outcome. If the link is incapable of furnishing the required S/N ratio, poor performance by all of the systems being evaluated is inescapable. On the other hand, if the tests were conducted under controlled laboratory conditions (as they were in the case of the acceptance tests for the KATHRYN and DEFT equipments), the absolute error rates are quite predictable and meaningful. The theoretical capabilities of all of the PSK systems which fall into the general category of differentially coherent, phase quadrature PSK are not substantially different (assuming that other pertinent parameters such as phase margins, symbol lengths, etc., are equal or nearly so).

It is, therefore, in the areas where noise is not the controlling factor that we would expect differences in performance to become evident, especially if one system incorporates provisions to combat a particular anomaly where another has not. It was the intention, of course, to achieve just such an advantage with the DEFT and KATHRYN systems, which were both designed with large amounts of multipath protection. However, as previously mentioned, the HF link itself proved to be an inadequate test bed for evaluation of these particular protective features. Although multipath was almost always evident, to some degree, the differential between paths was rarely greater than 1 to 2 milliseconds and was easily accommodated by all systems tested. This radio path has experienced very long multipath (often greater than 5 milliseconds and, on occasions, peaking greater than 12 milliseconds) in years when the ionosphere is more densely ionized. Therefore, the multipath protective features of the new modems must be regarded as necessary additions which will require evaluation under suitable conditions.

Another anomaly frequently experienced on transequatorial circuits during periods of higher sunspot activity, particularly during so-called

"Spread-F" propagational disturbances, is large differential multipath accompanied by rapid "flutter" fading (sometimes approximately 50 fades per second). Such conditions would certainly spell trouble for the "time differential" systems such as KATHRYN or KINEPLEX. A system such as DEFT should not be as vulnerable to these phenomena because of its long symbol length and real-time, frequency differential phase references, unless the correlation bandwidth of the fading should be very narrow (e.g., less than 100 cycles/second). There is, however, no evidence to substantiate this. Although very rapid (flutter) fading was not evident during these tests, observed fading was sufficiently rapid at times to necessitate a field change in the KATHRYN equipment in order to reduce the time differential between the reference signal and the new information to one bit length (26.6 milliseconds).

Since these field tests were conducted near the sunspot minima, the advantages of aforementioned protective features of the new systems could not be shown. It must be concluded that, in the absence of rapid fading and relatively long differential multipath delays, one might not expect any great difference in performance between any of the quadrature PSK systems themselves or, in fact, between the PSK and the FSK systems, if they are considered on an equal energy per bit basis.

Because the HF field tests are limited as tools in evaluating the additional advantages of the new phase systems, the conclusions drawn from these tests must be limited to a general consideration of performance in a highly perturbed, unpredictable medium.

The absolute error rate performance should not be taken out of context and applied to some other link. The circuit chosen was a long and difficult one, with operational difficulties, frequent QRM, occasional periods of high atmospheric impulse noise, and limited periods of high signal strength, all of which contributed to the performance data. In a sense, the performance of the medium itself is reflected in the cumulative results (i.e., percentage of time a given BER or better is achieved). However, the comparative results taken at the same time, or nearly the same time, with precautions to assure that conditions were sufficiently similar over the test duration, are considered a valid barometer of comparative modem performance.

VALIDITY OF RESULTS WITH SCALED SYSTEMS

Because of economic considerations, the KATHRYN and DEFT developments were procured as quarter-scale systems from the bit rate standpoint (i.e., 750-bit/second feasibility modems were tested instead of 3000-bit/second full-scale systems). Whenever this type of testing is performed, the validity of the simulation and consequent extrapolation of results are, naturally, questioned. In particular, for scaled systems of the frequency division multiplexed (parallel channel) types, such as those tested, the question of additional crosstalk between channels on a full-scale system is certainly a pertinent one. The problem of extrapolation with the FSK systems, such as the FGC-61A, is not as difficult as with the PSK systems, since the FSK channels are not as closely spaced as are the frequency orthogonal PSK channels. Each channel of FSK, based on the C.C.I.T. standards, is separated from its nearest adjacent neighboring channel by 170 cps. Since the maximum shift is $\pm$ 42.5 cps, there is an 85-cps frequency guard band (FGC) between channels to accommodate crosstalk. With the frequency orthogonal PSK systems, the channels are closely packed. The spacing between them is(1/T cycles/second), where T is the demodulation integration interval. Since minimum crosstalk between channels (e.g., f_1 and f_2) depends on a cross-correlation coefficient near zero, i.e.,

$$\int_0^T f_1(t)f_2(t)dt = 0,$$

then any disturbance (such as multipath distortion) which alters the length T introduces an additional misframing crosstalk. This is added to the usual cross-modulation and intermodulation products which may be present.

This type of additional crosstalk is precluded (in case of small differential delays) in the KATHRYN and KINEPLEX systems by use of a time guard band (TGB) of several milliseconds which prevents symbol "smearing" from entering the demodulation integration aperture. In the case of the DEFT system, crosstalk between groups is limited by shaping in a group filtering system which precedes the group correlators. The abbreviated DEFT system tested employed two groups (375 cps wide), situated at each end of the audio baseband (375 to 750 cps and 2625 to 3000 cps). In addition, all CW reference tones were transmitted between these groups every 125 cps. An analysis of the DEFT crosstalk problem shows that, with 2 milliseconds of differential multipath delay and 15-db actual S/N, the S/N would be degraded about 0.8 db when the system is expanded to full-scale. If this deterioration, the result of differential delay, is considered undesirable, the inclusion of a TGB may be appropriate.

The validity of scaling results experienced with the KATHRYN and KINEPLEX systems is not as subject to question as those obtained with the DEFT equipment, since a larger percentage of the signalling tones were transmitted. In the case of KINEPLEX, 16 of a possible 20 tones (3000 bits/second) were transmitted, whereas the KATHRYN system transmitted 24 of a possible 40 tones. In addition, the TGB, 4.2 milliseconds for KINEPLEX and 6.7 milliseconds for KATHRYN, provided protection against degradation from loss of orthogonality in this test since the observed multipath was rarely greater than 1 or 2 milliseconds.

Further laboratory investigation of the susceptability of DEFT to misframing crosstalk because of multipath smearing would be desirable. Initial testing by deliberately misframing to simulate multipath interference has indicated no serious degradation of performance. Further laboratory measurements using multipath simulation should be conducted to fully evaluate the extent of this misframing degradation.

In any event, crosstalk effects can be alleviated by inclusion of a TGB at the expense of a small amount of bandwidth economy. Such a change, if found necessary, would not detract from the error rate performance achieved by the DEFT system in these field tests (4 milliseconds of TGB can be achieved by changing the tone spacing from 25 to 27.8 cps).

INTERPRETATION OF THE RESULTS

General

The test results presented and discussed in Section IV are indicative of the relative performances of the modem systems tested. The reasons for these performances are often not apparent, since the presentation of "cause and effect" data is beyond the scope of this report. Some general observations relative to each modem system are appropriate in order to provide useful guidelines for the interpretation of these results.

The Collins KINEPLEX System, Model TE-202

This time-differential, coherent PSK system performed quite well, as indicated by the curves of Section IV. Since the TE-202 has been an "off-the-shelf" item for several years and has had ample time for "debugging," comparatively good performance under mildly perturbed conditions was expected and experienced. It was expected that the situations which would adversely affect this system would be those of extremely fast flutter fading (30 to 50 fades/second) and differential multipath delays exceeding 4 milliseconds. These situations were not encountered to any appreciable degree during the test; consequently, system performance could not be evaluated during these extremes. Inspection of test data has not revealed any advantage of this system over any other system during periods of "in-band" interference (QRM) or during atmospheric impulse disturbances (QRN).

The TE-202 and the N.R./Rixon FSK system were used as comparison standards for the new developmental systems. Although they were operated at 1200 and 900 bits/second, respectively, while the two experimental models were run at 750 bits/second, all systems were operated on an equal energy per bit basis in order to evaluate their relative performances at 3000 bits/second.

The TE-202 signalling spectrum extends from 605 to 2695 cps, with a synchronization tone at 2915 cps. This system is designed to keep the signalling channels well removed from the edges of the voice frequency baseband where the amplitude and phase response of terminal equipments may be troublesome. The TE-202 was out of service for one day during the test period because of equipment malfunction.

Based on the outcome of these evaluation tests, the TE-202 KINEPLEX modem system, although not new, performed nearly as well as the new DEFT development model and slightly better than the FGC-61A/Rixon Sepath combination on an equal energy per bit basis. This performance, which was accomplished at a bit rate of 1200 bits/second, can be extrapolated to a 300-bit/second parallel channel system without significant changes in the results. The basic conclusions regarding the TE-202 are:

(a) As a moderate speed modem (1200 to 3000 bits/second), its performance is obviously good, but not significantly better than the 42.5-cps shift FSK on an equal energy per bit basis.

(b) This system is not expandable beyond 3200 bits/second in a nominal 3-kc bandwidth without major changes in the modulation technique (e.g., changing to 8 phase positions which would result in only a 22.5-degree decision margin). Such a change does not appear feasible for use on long-range fading HF channels.

(c) Expansion potential for significant improvement of data quality (while maintaining a "through-put" rate of 3000 bits/second) by the application of error detection/correction coding techniques would be limited.

(d) The multipath distortion encountered on this path during the test period was successfully accommodated.

N.R. FGC-61A/Rixon Sepath High-Speed FSK System

Inspection of the comparative results shows that this modem combination also performed quite well and verifies the conclusion that within its bandwidth economy limitations, the audio frequency shift (AFSK) multiplexed tone technique is quite effective in the HF propagation environment.

It should be pointed out that this modem is really a "hybrid" system modem made up of a 12-channel AFSK tone multiplexed telegraph terminal, manufactured by Northern Radio Company, and a Rixon Sepath Converter (a serial-to-parallel/parallel-to-serial terminal equipment and associated bit timing synchronization equipment). Despite the usual interface problems and the fact that the apparatus was operated and maintained by personnel relatively unfamiliar with it, the combined system ran exceedingly well with a minimum of downtime because of equipment malfunction. The Rixon synchronizing circuiting achieved "lock-on" rapidly and without difficulty.

The basic conclusions pertinent to this system are:

(a) On an equal energy per bit basis, the results demonstrated good performance, but not quite as good as the PSK technique used in KINEPLEX and DEFT.

(b) The system is limited to 1200 bits/second in nominal 3-kc bandwidth compared with the higher bit capacities possible with the PSK systems.

(c) If 1200 bits/second is sufficient to meet data rate requirements and if error control coding is not required, this FSK method should perform nearly as well as the more complex PSK systems.

(d) The techniques required for expansion beyond 1200 bits/second within the same bandwidth occupancy are not applicable or feasible for use on fading HF radio channels (e.g., four-level or short symbol FSK).

The General Dynamics/Electronics DEFT System

Inspection of all the test results shows a consistent trend favoring this modem system over all others tested. The margin of performance over the TE-202 and the FGC-61A/Sepath equipments is not great and, in fact, would not be expected under the mild multipath conditions encountered. Had the differential multipath delays been 5 milliseconds or so, as is sometimes observed by the commercial stations using trans-equatorial circuits under conditions of high sunspot activity and Spread-F phenomena, a larger margin of improvement might have been observed because of the protective features inherent in DEFT.

It should be pointed out that, in a sense, the two DEFT groups located adjacent to the extremities of the voice band (375 and 3000 cps) represent a "worst case" condition in terms of vulnerability to phase distortion introduced by conventional radio transmission and receiving equipment. (Note: KINEPLEX purposely avoids these regions by moving inward to 605 and 2695 cps at the extremities.)

The DEFT modem was developed with many features applicable to HF radio transmission. Some of these features (e.g., dual diversity reception and frequency division multiplex-long symbol transmission) are common to almost all modems designed for HF radio. The techniques of employing phase quadrature modulation on two closely spaced tones to achieve a very long coded symbol for multipath protection and that of employing frequency differential real-time coherent detection for fast fading protection were new features included as part of this development. As previously indicated, the absence of long multipath precluded the evaluation of this specific advantage.

Another feature inherent in this system, and which can be exploited in any final system, is the high data "packing" density realized through closely spaced orthogonal channels together with symbol coding. By encoding 4 bits per symbol, 4000 bits/second can be sent in a nominal 3-kc bandwidth (at a small penalty in system performance versus S/N ratio). High-capacity systems have the option of operating at moderate data throughput rates, with many bits left over for protective coding for additional improvement.

The conclusions applicable to DEFT are:

(a) DEFT has a slight performance edge over KINEPLEX and the FGC-61A FSK modem and a decided margin over KATHRYN.

(b) The ability of the DEFT technique, with its lengthy symbol and real-time phase reference, to cope with long differential multipath delay and a rapidly fading environment could not be fully evaluated since such conditions were not experienced to any appreciable degree.

(c) The DEFT technique shows promise for expansion to a high-speed system with protective coding because of its high capacity potential (4000 bits/second in 2625 cps with no TGB, or 3000 bits/second in 2400 cps with a 7-ms TGB).

(d) This feasibility model, although still in an experimental stage, performed with a minimum of equipment failures during both tests and required the least amount of maintenance and adjustment of any of the systems tested.

(e) The bit timing synchronization subsystem consistently achieved "lock-on" rapidly and without difficulty.

(f) Because of the DEFT (higher order alphabet) encoding, time distribution of errors can be partially controlled for the effective use of protective coding by scrambling the bits contributing to the symbol. (Other higher order alphabet coded systems also have this capability to some extent, i.e., the greater the number of bits encoded on a symbol, the more flexible is the scrambling for controlling error distributions in the serial stream output.)

The General Atronics Simulated Extended Rate KATHRYN System (S-3000X)

This system was also developed with many features applicable to HF radio communications. A 6.6-ms TGB is used, as well as automatic phase and frequency control circuitry. Since the system is described in more detail elsewhere in this document, the details of the techniques employed will not be reiterated here; however, sophisticated and relatively complicated signalling processes are used which lend themselves to matching the characteristics of the propagation medium. These techniques require stable operation of several devices; e.g., circulating delay lines, crystal ovens, various feedback loops, etc., which made the experimental equipment extremely critical and difficult to maintain in the field. As a result, the equipment appeared to be in difficulty during a significant portion of the test. As a consequence, unless the malfunction was catastrophic, it was often impossible to isolate poor performance resulting from shortcomings of the technique and that caused by marginal equipment performance.

Although the results show the KATHRYN system with consistently poorer performance than experienced by the other systems, theoretical considerations indicate that it should have behaved in a similar fashion to the others tested. The fact that several test runs with sufficiently similar environmental conditions often showed inconsistencies in behavior (e.g., periods of good performances could not be repeated under similar conditions) appears to indicate marginal equipment performance rather than faulty technique. Because of the limited test time available on the leased channels during this field test, it was not possible to run the type of controlled test necessary to truly isolate the effects of each individual technique. Such an evaluation may need to be conducted with a controlled laboratory test under simulated conditions resembling those encountered in the field.

Under laboratory controlled acceptance tests, the KATHRYN equipment was subjected to a band limited, Gaussian distributed noise environment and met the expected error performance requirements under these conditions. The equipment was not militarized but was of good commercial grade and was not expected to have as many difficulties as were encountered.

APPENDIX

EQUATING TEST MODEMS ON AN ENERGY PER BIT BASIS

INTRODUCTION

Since bit rates and/or energy utilization differed for the various modems, it was necessary to determine the energy per bit for each modem as a function of total transmitter power. By adjusting the audio aggregate output level of each modem at the transmitting terminal with respect to 0 dbm (1 milliwatt into 600 ohms), the transmitter power for each system was controlled so that the system was radiating on an equal energy per bit basis. The energy per bit calculations for each modem are shown below.

COLLINS' KINEPLEX (1200 bits/second)

This modem contained 16 channels (8 channels transmitting data and 8 channels in a continuous [CW] state). The total power utilized in the system is:

$$P_{total} = 16\ P,$$

where P = power in a channel.

Each transmitted baud or symbol (13.3 ms) contains two bits of information; therefore, the energy per bit is:

$$\begin{aligned}\text{Energy/bit} &= \tfrac{1}{2} \times P \times 13.3 \times 10^{-3} \text{ watt-sec.}\\ &= 6.66 \times 10^{-3}\ P \text{ watt-sec.}\end{aligned}$$

The energy per bit in terms of the transmitter power available, P_{total}, is then:

$$\begin{aligned}\text{Energy/bit} &= \frac{1}{16} \times 6.66 \times 10^{-3}\ P_{total} \text{ watt-sec.}\\ &= 4.16 \times 10^{-4}\ P_{total} \text{ watt-sec.}\end{aligned}$$

NORTHERN RADIO/RIXON FSK MODEM (900 bits/second)

This modem also contained 16 parallel channels (12 channels transmitting data and 4 continuous channels). As in KINEPLEX, the total power is:

$$P_{total} = 16P .$$

Since only one bit is transmitted per symbol and the symbol length is 13.3 ms, the energy per bit is:

$$\text{Energy/bit} = P \times 13.3 \times 10^{-3} \text{ watt-sec.}$$

The energy per bit in terms of available power is:

$$\text{Energy/bit} = \frac{1}{16} \times 13.3 \times 10^{-3} P_{total} \text{ watt-sec.}$$

$$= 8.33 \times 10^{-4} P_{total} \text{ watt-sec.}$$

GENERAL ATRONICS SIMULATED EXTENDED RATE KATHRYN MODEM

Twenty-four tones are transmitted in this modem system. Ten channels contain information and phase reference quadrature components and ten others contain information and unused phase reference as their quadrature components. Of the remaining four tones, two are used as synchronization tones and the other two are transmitted as CW tones. Therefore, the total power is:

$$P_{total} = 24P,$$

where P = power/channel.

However, since half of the power is wasted in the channels with the unused phase quadrature component and since two sync tones can be used in the full-scale system (40 tones), the power used is:

$$P_{used} = 10P + \tfrac{1}{2} \times 10P + \frac{20}{40} \times 2P$$

$$= 16P.$$

There are 20 data channels with 1 bit per channel and an effective symbol length of 20 ms (although the fundamental symbol length is 26.6 ms, 6.6 ms, is not utilized). The energy per bit is:

$$\text{Energy/bit} = \frac{16}{20} P \times 20 \times 10^{-3} \text{ watt-sec.}$$

$$= 16 \times 10^{-3} P \text{ watt-sec.}$$

In terms of P_{total}, the energy per bit is:

$$\text{Energy/bit} = \frac{16}{24} \times 10^{-3} P_{total} \text{ watt-sec.}$$

$$= 6.67 \times 10^{-3} P_{total} \text{ watt-sec.}$$

GENERAL DYNAMICS DEFT

In the DEFT modem, 10 data channels (10 tone pairs), 22 reference tones and 2 synchronization tones are used. Each reference tone has twice the power of a channel tone pair, while each synchronizing tone has the same amount of power as a channel tone pair. Therefore, the total power is:

$$P_{total} = 10P + 22 \times 2P + 2 \times P,$$

where P = power in a channel tone pair = 56P.

Since the 22 reference and 2 sync tones will be required for the full-scale, 40-channel system, the necessary or used power for the 750-bit/second system is:

$$P_{used} = 10 \times P + \frac{10}{40} \times 22 \times 2P + \frac{10}{40} \times 2 \times P$$

$$= 21.5P .$$

Since within the 10 data channels 3 data bits are encoded in each 40-ms transmitted symbol, the energy per bit is:

$$\text{Energy/bit} = \frac{1}{3} \times \frac{21.5}{10} P \times 40 \times 10^{-3} \text{ watt-sec.}$$

$$= 28.6 \times 10^{-3} P \text{ watt-sec.}$$

In terms of the power available, the energy per bit for this system is:

$$\text{Energy/bit} = \frac{28.6}{56} \times 10^{-3} P_{total} \text{ watt-sec.}$$

$$= 5.12 \times 10^{-4} P_{total} \text{ watt-sec.}$$

Since the available transmitter power, P_{total}, is the same for all systems, it is possible to equate all systems on an energy per bit basis by penalizing all systems with respect to the system having the lowest inherent energy per bit (the reference) as shown in Table II.

Table II

Modem Level Settings for Equal Energy per Bit

System	Energy/Bit (watt/sec.)	Penalty (db)	RMS Volts* Across 600Ω
KINEPLEX	4.16 $P_{total} \times 10^{-4}$	(Reference)	0.775
DEFT	5.12 "	-0.9	0.698
Sim. KATHRYN	6.67 "	-2.0	0.615
N.R./Rixon	8.33 "	-3.0	0.548

*Measured with a Ballantine Model 320 True RMS Voltmeter

BIBLIOGRAPHY

Calvert, W., Equatorial Spread-F, NBS Technical Note 145, 1 August 1962.

DEFT High Capacity Telegraph Terminal Equipment, General Dynamics/ Electronics (1962).

DEFT Model SC-302 Operation and Maintenance Manual, ESD Contract No. AF 19(628)-3268, 28 February 1964

Equipment for Real-Time Data Transmission Over H. F. Radio Communications Circuits, DD 613 Project Card, Project 8938 (1962).

Hansen, J. C., High Frequency Radio Data Transmission Through Multipath Disturbance, ESD-TDR-62-327, December 1962.

Herman, J. R., Research on Spread-F Studies, Final Report, AVCO Corp., Technical Report RAD-TR-64-9, Contract AF 19(628)-2788, Project No. 4603, Task No. 460304, 31 January 1964.

Hinchman, W. R., et al., Analysis of Techniques for High Rate Data Transmission Over AMR H. F. Circuits, NBS Report 7288 (1962).

Instruction Manual for Feasibility Model Digital Data Transmission Terminal Equipment, Vols. I and II, General Atronics Corp., Contract No. AF 19(628)-3281.

Steinberg, B. D., KATHRYN, a Flexible Data Rate, Redundant Communication System, General Atronics Report 695-98-103 (1960).

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13. ABSTRACT

The comparative performance of several digital data modems over a high-frequency (HF) radio link is described in this document. During April and June 1964, field testing of evaluation models of new phase-shift keyed (PSK) modems was conducted over a leased 6900-nautical mile HF radio circuit from Pretoria, South Africa to Riverhead, New York. The superior bandwidth economy of PSK over frequency-shift keyed (FSK) modulation was demonstrated. This work was accomplished as part of the ESD program to improve missile test range HF digital data transmission.

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